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Instrumentation at the National Center for Asphalt Technology Test Track

Reed B. Freeman, H. Tommy Carr, Tom McEwen,
and R. Buzz Powell

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by   Reed B. Freeman

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

H. Tommy Carr

Information Technology Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Tom McEwen

1126 Garner Road
Summit, MS 39666-8028

R. Buzz Powell

National Center for Asphalt Technology
277 Technology Parkway
Auburn, AL 36830-0500

Final report

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Preface

1   Introduction

Background

The National Center for Asphalt Technology (NCAT) completed construction of an oval test track during the year 2000. The Engineer Research and Development Center (ERDC) assisted with the installation of instrumentation between November 1999 and September 2000. Moisture probes were installed in the improved roadbed subgrade and temperature probes were installed in the asphalt concrete. The purpose of this report is to document the installation of the probes and to present initial environmental measurement data.

The test track is oval in shape, with a total centerline length of 2.7 km (1.7 miles) (Photo 1). The track is located on 309 acres of land in Opelika, Alabama, approximately 20 miles from Auburn University. The purpose of the track is to study asphalt concrete mixtures. Therefore, the track was designed to be extremely stiff (AASHTO structural number = 10.8), so that pavement rutting failures would occur in the top 75 to 100 mm (3 to 4 in.) of asphalt concrete. Nine different state Departments of Transportation (DOTs) and the Federal Highway Administration (FHWA) all provided funding so that they could each participate in the design of asphalt concrete mixtures for specific pavement test items. Traffic is applied with triple-trailer trucks, traveling in a counter-clockwise direction (Photo 2). Within two years, the trucks will have applied 10 million equivalent single-axle loads (ESALs).

The general layout of track test items is shown in Figure 1, along with the locations of the laboratory and the portable asphalt drum-mix plant that was used during paving operations. A schematic drawing of a typical pavement cross-section is shown in Figure 2. The foundation soil consisted of red micaceous clayey silt or bedrock. The select fill consisted of the same silt blended with sedimentary rock with a maximum size of approximately 100 mm (4 in.). All pavement layers up to the experimental asphalt concrete surface course (i.e., top 75 to 100 mm) remained the same all the way around the track. The experimental surface course was different for each pavement test item and was designed with input from the participating state DOTs and the FHWA.

Description of Probes

One type of temperature probe was installed: the Model 108 temperature probe, manufactured by Campbell Scientific, Inc. These probes were designed for use in air, soil, and water (Campbell Scientific, Inc. 1996). They cost approximately $70 each plus $1.00 per meter of cable. The thermistor in each probe is protected within a rigid casing approximately 125 mm (5 in.) in length and 6 mm (1/4 in.) in diameter (Photo 3). While cable lead lengths of up to 305 m (1000 ft) are permissible, lengths over 91 m (300 ft) require programming adjustments for increased measurement times. The probes' acceptable temperature measurement range is -5°C to 95°C (23°F to 203°F) and their survival temperature range is -50°C to 100°C (-58°F to 212°F). The overall probe accuracy is a combination of the thermistors' interchangeability specification, the precision of the probes' bridge resistors, and the error associated with the fifth-degree polynomial used to convert raw voltage measurements to temperatures. All errors considered, accuracy of these probes remains ±0.3°C over the range of -3°C to 90°C and ±0.7°C over the range of -5°C to 95°C (Campbell Scientific, Inc. 1996).

Two types of moisture probes were installed: Model CS615 probes purchased from Campbell Scientific, Inc. and Model Sentry 200 probes purchased from Troxler Electronic Laboratories, Inc., Troxler International, Ltd. (Photo 4). The CS615 probes cost approximately $200 each, with a cable cost of approximately $2.00 per meter. The Sentry 200 probes cost approximately $900 each, with a cable cost of approximately $2.00 per meter.

Both types of probes detect changes in moisture by detecting changes in the dielectric constant of materials. Most solid materials in soil, such as sand, clay, and organic matter have dielectric constants from 2 to 4. Water, however, has a much higher dielectric constant of 78 (Campbell Scientific, Inc. 1997). Thus, increases in the moisture content of soil can be identified by measured increases in the soil's dielectric constant.

The Campbell Scientific probes, which are sometimes referred to as water content reflectometers, use time-domain measurement methods. The probes consist of two stainless steel rods connected to a printed circuit board, which is encapsulated in epoxy (Photo 4). The rods are 300 mm (12 in.) long and 3.2 mm (1/8 in.) in diameter. They are parallel and are separated by a distance of approximately 50 mm (2 in.). The epoxy block is 110 mm (4.3 in.) long, 63 mm (2.5 in.) wide, and 20 mm (0.8 in) thick. High-speed electronic components on the circuit board are configured as a multivibrator. Output from the multivibrator is transmitted to the rods, which then act as vibration wave guides. The travel time for waves along the rods is dependent on the dielectric constant of the materials surrounding the rods. Readings are affected primarily by material that is between the rods; the effective radius of influential materials can be considered as approximately 50 mm (2 in.). Typical accuracy for these probes is ±2.0 percent moisture by volume if the probes are calibrated for a specific soil (Campbell Scientific, Inc. 1997).

The Troxler probes estimate moisture by measuring a frequency shift for electromagnetic waves. The electromagnetic waves are generated by two electrical components, which are separated by an insulating spacer. The probes are composed of stainless steel, polypropylene, and fiberglass epoxy. They are cylindrical in shape, with lengths of 260 mm (10 in.) and maximum diameters of 50 mm (2 in.) (Photo 4). These probes are sleek and they do not have any protruding rods, so they are rugged and they are easily inserted into drilled holes. Readings are influenced by material that is within a radius of approximately 100 mm (4 in.). Assuming proper calibration and installation, accuracy is expected to be ±2.5 percent by volume (Troxler Electronic Laboratories, Inc. 1992).

General Instrumentation Layout

The moisture probes were installed at one depth: 100 mm (4 in.) below the top of the select fill. Moisture probes were placed at every second intersection between test items, as shown by the locations of 23 data assimilation stations in Figure 3. A single Campbell Scientific probe was installed at each data assimilation station, positioned in the center of the outside traffic lane. Three Troxler probes were installed at each of two data assimilation stations, as shown in Figure 3. Two of these probes were also positioned in the center of the outside lane and one probe was positioned at the intersection between the outer lane and the shoulder.

Four temperature probes were placed in every test section, within 6 m (20 ft) of the data assimilation stations. The temperature probes were installed at four different depths within the asphalt concrete, ranging from the bottom of the upper asphalt binder course to the pavement surface. Probes placed at the bottom of the binder course and at the top of the binder course were positioned in the center of the outside traffic lane. Probes placed at the middle of the experimental mix and at the pavement surface were positioned 0.3 m (1 ft) inside the outer edge of the outside traffic lane.

Data Assimilation Hardware

Each data assimilation station included a weatherproof enclosure, provided by Campbell Scientific. These enclosures were attached to test section signposts, directly behind the signs, as shown in Photo 5. Two of the 23 stations were also equipped with a Troxler enclosure. These enclosures were also attached to the signposts, as shown in Photo 5.

Each Campbell Scientific enclosure included three components (Photo 6): a power system, a Model CR10X datalogger and an MD9 multidrop interface. The power system included the use of a solar panel, which was mounted to the top of the signpost. The dataloggers served as self-contained, programmable data acquisition systems. They excited gages, collected data, and conditioned signals.

Each datalogger also included a back-up power supply. The multidrop interfaces were necessary for communicating data back to data acquisitions computers, which were housed in the track laboratory. A desiccant pack was placed in each enclosure; packs are to be replaced every 3 to 6 months. Each data assimilation station was also equipped with a 2.4-m (8-ft) copper-clad grounding rod. The total cost for each station, including enclosure, solar panel, and grounding rod, was approximately $2000.

Each Troxler enclosure included a power system and a Troxler ProbeReader Plus data acquisition system (Photo 7). The cost of each Troxler enclosure was approximately $5000.

All Campbell Scientific probes (including temperature and moisture) were connected directly to the CR10X dataloggers. The Troxler moisture probes were connected to a Troxler ProbeReader Plus, which was connected in-turn to the CR10X that occupied the same signpost.

Stations were connected to data collection computers in the on-site laboratory via coaxial cables, which were buried and were protected in 32-mm (1.25-in.) O.D. PVC conduit. The conduit actually contained two cables, with one serving as a back-up. The data assimilation stations were linked as two completely separate "daisy chains." Each chain required approximately 1700 m (5600 ft) of cable and was provided with its own data collection computer. One chain (called the "North leg") included all test sections in the north tangent and most test sections in the west curve (W1 through W9) (Figure 3). The other chain (called the "South leg") included all test sections in the east curve, all test sections in the south tangent, and one test section in the west curve (W10). Two legs were necessary to limit cable lengths and had the advantage of minimizing loss in the case of lightning strike. The contracted price for installing the coaxial cables was approximately $50,000.

Each data collection computer is equipped with Campbell Scientific software named PC208, which serves as an interface to each data assimilation station. The software can call each station individually using its unique MD9 multidrop interface address. Using this software, the user can program all CR10X dataloggers from the central computer location. The user can also program a schedule for intermittent data calls. During each data call, the computers retrieve data that is temporarily stored in the dataloggers.

2   Laboratory Calibration

Temperature Probes

Calibration of these probes was deemed unnecessary. These probes are designed to be interchangeable and they are all sold with a common equation to be used for converting voltage measurements to temperature measurements. Unlike the moisture probes, the temperature probes do not need to be calibrated for the particular environment in which they are to be used.

In order to verify the accuracy of the probes and to demonstrate the consistency between probes, eight probes were placed in three water baths with known temperatures of 0.44°C (32.8°F), 23.8°C (74.9°F), and 59.3°C (138.8°F). Each probe was equipped with cable lengths of 15.2 to 30.5 m (50 to 100 ft). Three replicate temperature measurements were obtained for each probe in each bath. Replicate measurements were obtained during a single immersion. The average temperatures that were measured by probes are shown in Table 1. An analysis of variance was performed for data obtained with each temperature bath. In each analysis, the different probes were the treatment factor, as shown in Tables A1, A2, and A3. The magnitudes of probe and replicate variability for temperature measurements are shown in Table 2. For data obtained with each temperature bath, the standard deviations of temperature measurements between probes, between replicates, and total were all less than or equal to 0.06°C (0.11°F). Measured temperatures matched the bath temperatures very well (Figure 4). To test the interchangeability of the probes, a linear regression was conducted with both bath temperature and probe number as fixed independent variables. Student's t-tests found probe number to have an insignificant effect on the model (Table 3). In summary, the temperature probes were found to be repeatable, accurate, and interchangeable.

Moisture Probes

Both types of moisture probes were calibrated within the same material that was to be placed around the probes during their installation at the NCAT test track. This material consisted of the select fill used at the track, with large particles removed. Large particles were removed by passing the soil through a wire mesh with openings approximately the same size as a No. 4 sieve.

Campbell scientific probes

The Campbell Scientific probes were calibrated using soil with three target moisture contents: 0, 10, and 20 percent by mass. The soil was mixed at each of the three moisture contents and was compacted in a polyvinyl chloride (PVC) tube, which was approximately 400 mm (16 in.) tall and had an inside diameter of 150 mm (6 in.), as shown in Photo 8. The soil was compacted to achieve a density that would be similar to that which would be possible in the vicinity of the probes. The soil was compacted in three layers of equal thickness; each layer received 25 blows from a standard Proctor hammer.

To obtain the data necessary for calibration, each Campbell Scientific probe was used to measure moisture content for the soil in each of the PVC tubes. For each probe, the full length of the parallel, stainless steel rods was pushed into the soil in each PVC tube. Each Campbell Scientific probe was inserted into each tube of soil three times. This provided three replicates of raw data readings. Raw data readings represented the period of electromagnetic wave travel along the rods (ms). Moisture contents for the calibration soils were measured by oven-drying representative samples. The measured moisture contents for the tubes of soil were 0, 9.6, and 20.5 percent by mass.

The average probe measurements obtained during calibrations are shown in Table 4. The variability between replicate readings was small. The average and maximum coefficients of variation for replicate Campbell Scientific measurements were 1.6 percent and 5.9 percent, respectively.

The calibration equation for the Campbell Scientific probes has the form:

$$y = ax^2 + bx + c$$

where

   y = gravimetric moisture content (as a decimal)

   x = measured electromagnetic wave period (ms)

The calibration equation published by Campbell Scientific (Campbell Scientific, Inc. 1996) actually uses volumetric moisture content. Volumetric moisture content is proportional to gravimetric moisture content and can be calculated by multiplying gravimetric moisture content by the specific gravity of soil solids. Due to the common use of gravimetric moisture content in construction, gravimetric moisture content will be used in this report.

Calibration coefficients were obtained for each probe by determining the best-fit curve for a plot of probe measurement versus moisture content. These coefficients are shown in Table 5. Calibration coefficients were also determined for all the probe data when plotted collectively, as shown in Figure 5. These coefficients are included in Table 5 under the name "composite calibration." The first decision to be made is whether to use individual calibrations or the composite calibration. This decision should be based on the relative contri-

butions of measurement variability provided by both differences between probes and differences between replicates. Therefore, an analysis of variance was conducted for the probe measurement data that was obtained at each moisture content. These analyses are summarized in Tables A4 through A6. These analyses provided information related to two components of variance and their relative magnitudes, as shown in Table 6. The overall coefficient of variation between probe measurements was less than 3 percent for each moisture content. Also, the total variance was divided approximately equally between probe variance and replicate variance. This information, along with the qualitative judgment of adequate composite curve fitting in Figure 5, resulted in the use of the composite calibration parameters. The Campbell Scientific probes behaved similarly, so they do not require individual calibrations.

Troxler probes

The Troxler probes were calibrated using soils with four target moisture contents: the as-received moisture content, 0, 15, and 20 percent moisture by mass. The soil was mixed at each of the four moisture contents and was compacted in 18.9-L (5-gal) plastic buckets, which were approximately 350 mm (14 in.) deep and had an inside diameter of 280 mm (11 in.), as shown in Photo 9. The soil was compacted in three layers of equal thickness using a 150-mm (6-in.) diameter Marshall hammer. The Marshall hammer was not raised and dropped in a standard manner. The entire device was lifted and dropped from heights of approximately 305 mm (12 in.). Each lift of material received approximately 25 blows by the hammer. This modified procedure served the primary objective, which was to compact the soil to a density similar to that, which would be obtained in the field.

To obtain the data necessary for calibration, each Troxler probe was used to measure moisture content for the soil in each of the plastic buckets. The full length of each probe was inserted into holes in the soil, which were created using a hand-auger. Soil was compacted around the probes near the soil surface to ensure good contact. While each probe was buried in each bucket, three readings were obtained, providing three replicates of raw data readings. Raw data readings represented a difference between the measured frequency (1/s) of electromagnetic waves and that of a known standard. Moisture contents for the calibration soils were measured by oven-drying representative samples. The measured moisture contents for the buckets of soil were 0.0, 7.7, 14.0, and 19.9 percent by mass.

The average probe measurements that were obtained during calibrations are shown in Table 7. The variability between replicate readings was small. The average and maximum coefficients of variation for replicate Troxler measurements were 0.02 percent and 0.12 percent, respectively. The variability between replicates was lower for Troxler probes than for Campbell Scientific probes. The most likely cause for this difference was that while the Troxler replicates were obtained during a single probe installation, the Campbell Scientific probes were removed and reinstalled for each replicate.

The calibration equation for the Troxler probes has the form:

$$y = \left(\frac{1}{C1}\right) \ln\left[\frac{(x - C2)}{C0}\right]$$

where

y = gravimetric moisture content (as a percent)

x = measured electromagnetic wave frequency difference from a standard (1/s)

Similar to the procedure used for the Campbell Scientific probes, calibration coefficients were obtained for each probe by determining the best-fit curve for a plot of probe measurement versus moisture content. These coefficients are shown in Table 8. Calibration coefficients were also determined for all the probe data when plotted collectively, as shown in Figure 6. These coefficients are included in Table 8 under the name, "composite calibration." The analyses of variance for probe measurement data are summarized in Tables A7 through A10. A separate analysis was conducted for data obtained at each calibration moisture content. These analyses provided information related to two components of variance and their relative magnitudes, as shown in Table 9. The overall coefficient of variation between probe measurements was greater than 6 percent at each moisture content. Also, the total variance was almost entirely attributable to variability between probes. This information, along with the qualitative judgment of poor composite curve fitting in Figure 6, resulted in the use of individual probe calibration parameters. In summary, individual Troxler probes behaved sufficiently different from each other to exclude the possibility of using a composite calibration.

Comments on moisture calibrations

The user's manuals that accompany both Campbell Scientific and Troxler moisture probes urge users to calibrate the probes with the particular soil that is to be instrumented. The data in this study demonstrates the importance of this practice. For the CS615 probes, Figure 7 compares the calibrations produced in this study with the standard calibrations that are offered in the user's manual. The range of standard calibrations shown in the figure reflects the range of electrical conductivities for different soils. Figure 8 compares the factory calibration for Troxler Probe No. 3 with the calibration produced specifically for the soil used at the NCAT Test Track. Probe No. 3 serves as an example in this case; each probe needed its own calibration. The accuracy of moisture measurements were improved for both the Campbell Scientific and Troxler probes by implementing soil-specific calibrations. Improved accuracy was most significant at higher moisture contents.

Although the soil-specific calibrations improved the accuracy of moisture measurements, the calibration coefficients presented in this chapter (Tables 5 and 8) are not the final coefficients. A final adjustment was made at the time of

installing the probes at the test track. This adjustment, which will be described in Chapter 4, will be made possible by comparing initial probe measurements with soil moistures determined by oven drying.

3 Field Installation

Moisture Probes

At the time of installing the moisture probes, the 0.15-m- (6-in.-) thick crushed granite base course was already in-place. Therefore, at each designated probe location, a hole was dug through the base and 0.125 m (5 in.) into the select fill. Shallow trenches, reaching a depth of one-half base thickness were also required to run cables to the pavement edge. Placements of Campbell Scientific CS615 probes required only a single, straight trench (Photo 10). The probes were positioned at the center of the outer traffic lane. Placements that involved both a CS615 probe and three Troxler Sentry 200 probes required a "T-shaped" trench (Photo 11). The CS615 probe and two of the Sentry 200 probes were positioned at the center of the outer traffic lane. The CS615 resided in-between the Sentry 200 probes, at the center of the "T-shape." A Sentry 200 probe was then placed on each side of the CS615 probe, separated by a horizontal distance of approximately 0.9 m (3 ft). The third Sentry 200 probe was positioned 4.3 m (14 ft) from the pavement centerline, at the intersection between the outer lane and the shoulder. Installation procedures, which will be described in the following text, were the same for both types of moisture probes.

Two types of aggregate materials were processed in preparation for installing these probes. Select fill was scalped with a No. 4 sieve and the finer fraction was collected. The crushed granite used for base course was scalped with a No. 16 sieve and the finer fraction was collected. The fine fraction of select fill was the same material that was used for probe calibration. This material was placed around probes during installation. Large particles were removing to minimize risk of damaging probes and to improve efficiency of hand-compaction operations. The fine fraction of crushed granite was placed around cables that were buried with the pavement base course. Again, the removal of large particles minimized the risk of damaging cables.

Photo 12 shows a CS615 probe in its final destination. Care was taken to ensure that the cable had some slack. This practice minimizes the risk of cable damage due to tension. Photo 13 shows the same gage location after hand-compacting the fine-fraction select fill. After protecting the cable with fine-fraction crushed granite and after filling the trench with the base course material previously removed, the trench was compacted by both foot and truck tire traffic (Photo 14).

At the time of installing moisture probes, the pavement contractor was installing edge-drains. The longitudinal shoulder trench can be seen in Photo 14. The moisture probe cables needed protection while the contractors continued pavement construction. For the short-term, the ends of cables were waterproofed and the cables were placed under 19-L (5-gal) buckets. Once the edge-drain construction reached the top of the crushed granite base, the cables were extended through the edge-drains and across the shoulders. They were threaded through 25-mm (1-in.) O.D. PVC pipe (Photo 15). The cables remained in that condition until the pavement and shoulders were completed, at which time the cables were retrieved. To facilitate cable retrieval, a straight PVC pipe connection was positioned near the eventual location of the test section sign and the data assimilation hardware.

Temperature Probes

Temperature probes were installed during two phases. During the first phase, two thermistors were installed in the asphalt concrete binder course in each test section. These probes were positioned in the center of the outside traffic lane, one at the bottom of the binder course and one at the top of the binder course (Figure 9). During the second phase, two thermistors were installed in the experimental asphalt surface course mixture in each test section. These probes were positioned 0.3 m (1 ft) inside the shoulder stripe for the outside traffic lane, one placed at the middle of the experimental mix and one placed at the pavement surface.

All temperature probes were installed near the data assimilation stations, as presented in Chapter 1. Because each station was located at a transition between test sections, temperature probes connected to a single station could reach two test sections. Eight temperature probes were connected to each station, four reaching each of two test sections. The probes extended from the stations at approximate 45-degree angles, forming V-shaped patterns.

The installation process began when the last lift of asphalt binder course was being placed. Ropes were used to form cable trenches in the surface of the binder course. The ropes, which were approximately 25 mm (1 in.) in diameter, were laid onto the surface of asphalt immediately before rolling compaction. Rollers then pressed the ropes into the asphalt concrete, thus forming the trenches (Photo 16). While one end of the rope remained near the data assimilation station, the other end was positioned at the location where probes were to be installed. A knot was tied in the rope at the probe end in order to widen the trench in that particular area. After the asphalt cooled, the rope was removed from the asphalt concrete, leaving a clean and well-formed cable trench (Photo 17).

To reach the bottom of the binder course, a 13-mm- (0.5-in.-) diam hole was drilled with a hand-drill (Photo 18). A single probe was pushed into the hole and then the cable was strung along the trough. A second probe was placed near the hole, lying horizontally within the trough (Photo 19). A heavily polymer-

modified asphalt-based binder was used to fill the trough, securing the temperature probes and the cables. To reach flowable condition, the binder was heated to approximately 150°C (300°F). This high heat could damage thermistors, so the surface thermistor was covered with minus No. 16 crushed granite (Photo 20). Photo 21 shows the pouring of binder into a trough. Because the cables tended to float in the binder, they had to be secured within the trench. The best method for securing the cables was found to be U-shaped wire tacks. The pouring sequence for the binder was to first fill the vertical hole as well as possible. There was little space between the probe and the edge of the hole, so this did not require much binder. Then the pouring proceeded toward the data assimilation station. The trench was filled to level and then it was covered with the minus No. 16 crushed granite (Photo 22). After the binder cooled, excess aggregate was swept away and any substantial binder drip spots were removed with a hot flat plate (Photo 23). Note in Photo 23 that the temperature probe cables were threaded through a PVC pipe. Similar to the situation for the moisture probe cables, the temperature probe cables had to be protected during continued paving operations and shoulder construction. The PVC pipe was extended across the shoulder and then when the data assimilation station was set up, the temperature probe cables were retrieved from the pipe.

Probe installation in the experimental surface course mixtures was similar. One probe was installed in each test section during the placement of each of the two asphalt concrete lifts. No drilling was required. However, the color of the material used at the pavement surface became a concern for both aesthetic and measurement accuracy reasons. For each test section, a sample of the appropriate hot-mix was compacted over the temperature probe at the pavement surface (Photo 24). This practice ensured appropriate color and thermal conductivity. As an aesthetic improvement, the color of aggregate used at the pavement surface to protect trench-filling binder was darkened (Photo 25).

Additional Instrumentation

Two additional environment-related pieces of instrumentation were installed at the test track: a weather station and volume measurement devices for pavement drainage. These instruments were not part of this project, but will be mentioned for completeness. The weather station was positioned near the on-site laboratory at the NCAT test track (Photo 26). It measures air temperature, relative humidity, solar radiation, rainfall, wind speed, and wind direction. All components were purchased as a set from Campbell Scientific, Inc., at a cost of approximately $5,000. The contracted cost for assembling and installing the weather station was approximately $13,000.

The volume measurement devices, or tipping buckets, were necessary to obtain samples of the effectiveness of the test track subsurface drainage system. The subsurface drainage system included a permeable asphalt-treated base and standard edge-drains. The edge drains used both permeable aggregate and a 0.1-m- (4-in.-) diam perforated pipe. On the straight portions of the track, edge-drains were installed in both pavement shoulders. On the curved portions of the

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track, edge-drains were installed only in the inside shoulder. Edge-drain pipe outlets were installed at intervals of approximately 76 m (250 ft), as shown in Figure 10. The outlets consisted of rigid PVC pipes that extended laterally from the edge-drain pipes, to the ground surface above a drainage ditch. One outlet in the North tangent was equipped with a tipping bucket and two outlets in the South tangent were equipped with tipping buckets (Figure 10).

The tipping buckets were donated by the Mississippi Department of Transportation. Their design has origins in Wisconsin, so they are often referred to as "Wisconsin tipping buckets." The drainage outlet pipe connects to the top of the tipping bucket (Photo 27). As water enters the tipping bucket, it fills a bowl. Once the bowl fills with approximately 0.5 L of water, it tips over and empties. For flowing water conditions, the bowl repeatedly fills, tips, and empties. Calibration involves supplying a known flow and counting tips. Calibration provides the user with a precise volume of water per tip. In the field, tips are counted during pre-defined periods of time, thus providing the flow of water.

The tipping buckets at the NCAT test track are protected within prefabricated dog houses (Photo 28). A single wire connects each tipping bucket to a data logger at one of the data assimilation stations that is also used for temperature and moisture probes. The importance of the tipping bucket measurements can be seen in Photo 29, which shows water flow from a drainage outlet after a brief afternoon shower.

4 Probe Measurements at the Test Track

During Probe Installation

Moisture probes

Immediately after installing each moisture probe, probe output data were obtained using hand-held keyboard/display units provide by Campbell Scientific (Model CR10-KD). These data were obtained to ensure that the probes were functioning properly and also to permit final adjustments to calibrations. These adjustments were necessary to account for any slight differences between field and laboratory conditions, such as the level of compaction achieved in a shallow trench versus that achieved in a laboratory bucket. Samples of soil were also obtained during probe installation. Soil samples were obtained from the in-situ select fill that was exposed in the vicinity of the probe installation locations. Soil samples were also obtained from the scalped select fill that was placed around the probes during installation. The soil samples were later used to measure oven-dry moisture contents.

Data obtained during the installation of Campbell Scientific probes are shown in Table 10. These data include the probe measurements (with units of ms), the estimated moisture contents (using the composite calibration coefficients presented in Chapter 2), and the moisture contents measured by drying soil in an oven. Table 10 also shows the calculated differences between the moisture contents estimated by probes and the oven-dry moisture contents of scalped fill. On the average, probes estimated moisture contents to be 2.9 percent lower than that measured by oven drying. This average difference was expected to be a more accurate correction than individual measured differences. Errors contributed by soil sampling would tend to be minimized with the overall average difference. Also, the correction was intended to reflect primarily differences between field and laboratory conditions. These differences were expected to be similar for all probe installations.

Data obtained during the installation of Troxler probes are shown in Table 11. These data include the probe measurements (with units of 1/s), the estimated moisture contents (estimated using the calibration coefficients developed for individual probes), and the moisture contents measured by drying soil in an oven. Similar to Table 10, Table 11 also shows the calculated differences

between the moisture contents estimated by probes and the oven-dry moisture contents of scalped fill. On the average, probes estimated moisture contents to be 2.5 percent higher than that measured by oven drying. The moisture contents of in-situ select fill were not used for any calibration adjustments. They were obtained as a matter of interest.

The composite calibration for the Campbell Scientific probes was corrected by increasing parameter c by +0.029 (2.9 percent moisture). Neither parameter a nor parameter b was affected. The final adjusted moisture prediction equation is shown in Table 12, along with all final adjusted moisture content estimates.

The individual calibrations for the Troxler probes were corrected by multiplying parameter C0 by +exp(2.5*C1). Neither parameter C1 nor parameter C2 was affected. The final adjusted calibration coefficients for each probe are shown in Table 13. The final adjusted moisture content estimates are shown in Table 14.

Temperature probes

Temperature probe measurements were not recorded during installation because they were not needed for the purpose of adjusting calibration. However, temperatures were monitored during installation for the purpose of ensuring survivability. A probe could become ruined if its temperature exceeded approximately 120°C (250°F). After completing installation, each probed was checked to ensure that it was functioning properly.

Instantaneous Moisture Measurements

During pavement construction and prior to completing the entire network of instrumentation hardware, several instantaneous moisture measurements were obtained using the hand-held keyboard/display units. Measurements obtained from the CS615 probes are shown in Table 15, while those obtained from the Sentry 200 probes are shown in Table 16. It is apparent from both tables that moisture contents at the top of the select fill increased substantially from November 1999 to February and March 2000. After reaching levels between 20 and 25 percent, moisture contents stabilized. For a portion of the time between November 1999 and February 2000, the base was exposed. Also, the next constructed layer was permeable asphalt-stabilized base, which would still allow quick intrusion by rainfall.

It is apparent from Table 15 that moisture contents were relatively uniform around the track. It is apparent from Table 16 that moisture contents near the pavement shoulder were similar to those at the middle of the outside traffic lane.

Moisture contents in the range of 20 to 25 percent are near 100 percent saturation. This statement is based on the finding that laboratory soil samples could not be produced at moisture contents of 25 percent. At that degree of wetness,

the samples could not retain all their moisture. When compacting in containers, excess water would collect at the top of the sample. Also, records show the typical dry density for select fill to be about 1840 kg/m^3 (115 pcf). Assuming a specific gravity of solids of 2.9, 100 percent saturation should occur at moisture contents of approximately 20 percent.

Periodic Measurements

Once all the data acquisition software and hardware was installed, data acquisition became automatic. Dataloggers collect data once each minute, including:

    a.   Temperature (°F) for each temperature probe.

    b.   Raw data for each moisture probe (ms for CS615 and s^{-1} for Sentry 200).

    c.   Number of tips for the tipping bucket.

    d.   Enclosure temperature (°F).

    e.   Battery voltage (V).

All the dataloggers collect temperature measurements from each of eight probes. Twenty-one of the 23 dataloggers collect moisture measurements from only one CS615 probe. The remaining two dataloggers collect moisture measurements from four probes (one CS615 and three Sentry 200). Only three of the 23 data-loggers collect tipping bucket measurements.

At the end of each hour, the dataloggers summarize the one-minute-interval measurements for temperature and moisture with minimum, maximum, and average. For the tipping buckets, however, the one-minute-interval measure-ments are summed and the dataloggers convert total number of tips to hourly volume in liters. The dataloggers are programmed with the appropriate tipping bucket calibrations. For the moisture probes, the dataloggers convert raw data to moisture content using the appropriate calibrations. Moisture content is reported as a decimal for CS615 probes and as a percent for Sentry 200 probes.

The data acquisition computers retrieve data from the dataloggers once each hour and save the data to designated ASCII files. However, the computers can remain offline for up to approximately three months without causing the loss of any data. The dataloggers have sufficient memory to store summarized data for that period of time. The order of temperature probes in the data files, presented from left to right, is shown in Figure 11. The order of moisture probes in the data files, presented from left to right, is: the CS615 probe and then the three Sentry 200 probes. The Sentry 200 probes are presented in the following order: first, the probe at the shoulder/traffic lane interface and then two probes at the center of the outside traffic lane (in the same order that they are met by traffic).

Data from three dataloggers will be used in this report as the sources of example measurements. These dataloggers were selected because they are spread out around the track and each includes a tipping bucket. One datalogger is positioned between test sections N3 and N4, the second datalogger is positioned between test sections W10 and S1, and the third datalogger is positioned between test sections S8 and S9.

An example of temperature fluctuations at the pavement surface is shown in Figure 12. This particular probe is positioned at the surface of test section S1. Both seasonal and daily trends are apparent. During the month of December 2000, the temperature reached a minimum of approximately -6°C (21°F). During the month of June 2001, the temperature reached a maximum of 60°C (140°F).

Temperature fluctuations occurring over a single day in September 2000, and at four depths in the pavement, are shown in Figure 13. Temperatures at the pavement surface experienced the largest and quickest fluctuations. While temperatures at the pavement surface fluctuated from 20°C (68°F) to 50°C (122°F), temperatures at the bottom of the upper binder course fluctuated over a smaller range: 29°C (84°F) to 35°C (95°F). While temperatures at the pavement surface peaked at 1500 hr, temperatures at the bottom of the upper binder course didn't peak until 2000 hr.

Moisture trends from September 2000 to February 2001 are shown in Figure 14. Over the nine-month period, moisture contents in the select fill remained relatively constant. Moisture contents were also relatively uniform around the test track. Drainage outflow measurements from October 2000 to February 2001 are shown in Figure 15. Many rainfall events are evident for the month of November 2000. The outlet near test sections N3 and N4 appears to carry a relatively large flow of drainage water. This may be a characteristic of the pavement subsurface drainage patterns.

5 Summary and Lessons Learned

Summary

The pavement test track at the National Center for Asphalt Technology (NCAT) was successfully instrumented for temperature, moisture, and subsurface drainage flow. This effort was achieved through cooperation between NCAT, the Engineer Research and Development Center, and private consultants. Instrumentation hardware included 23 dataloggers spread out over the 2.7 km (1.7 miles) oval-shaped track and hard-wired to the on-site laboratory with 1700 m (5600 ft) of buried coaxial cable. Instruments included 184 temperature probes, 29 moisture probes, and three tipping buckets for measuring subsurface drainage flow. This report describes the hardware and documents both calibration and installation.

The temperature probes were Model 108 from Campbell Scientific, Inc. Moisture probes included CS615 probes from Campbell Scientific, Inc. and Sentry 200 probes from Troxler Electronic Laboratories, Inc., of Troxler International, Ltd. The tipping buckets were manufactured and donated by the Mississippi Department of Transportation.

Laboratory measurements verified that the temperature probes did not require individual calibrations; factory calibrations were accurate and sufficient. This study showed that the moisture probes required laboratory calibrations in the appropriate soil. While a single laboratory calibration applied to all CS615 probes, each Sentry 200 probe required an individual calibration. Slight adjustments in calibrations were necessary during probe installations and were achieved by comparing initial moisture measurements to oven-dry moisture contents for the surrounding soil.

Four temperature probes were installed in each of 46 pavement test sections. Probe depths ranged from the pavement surface to the bottom of the upper binder course. A CS615 moisture probe was installed at 23 locations, involving every second intersection between test sections. Three Sentry 200 moisture probes were installed at each of two locations. One tipping bucket was installed at each of three locations.

A moisture probe and several temperature probes were damaged during pavement construction operations and were subsequently replaced. All probes are now performing well. The Sentry 200 probes were installed so their performance could be compared to that of the CS615 probes. So far, their performance is similar.

Lessons Learned During Installation

The following lessons were learned during the installation of temperature probes.

a. Temperature probes should not be installed near transverse joints where lifts will be sawn and cut back. Cables can become damaged during blading operations used to remove asphalt concrete.

b. Temperature probe cable will float in liquid binder. If cable is to be set in troughs, the cable must be held in place with U-shaped tacks.

c. Temperature probes must be protected from temperatures exceeding 120°C (250°F). In this study, they were protected with a covering of fine aggregate.

d. After filling troughs with binder, they were immediately covered with fine aggregate. This prevented tracking the binder and may have also helped to prevent bleeding.

e. The temperature probe that resides in a trough at the pavement surface must be covered with a material that has the same color as the asphalt concrete wearing course. In this study, samples of the mix were saved and were reheated.

The following lessons were learned during the installation of moisture probes.

a. Produce plenty of pre-sieved fill material to be used for compacting around probes, so that on-site sieving does not slow installation procedures. The sieved material should not include particles larger than the No. 4 sieve and should be the same as that used for probe calibrations.

b. Produce plenty of pre-sieved fill material to be used to protect buried cables. Whenever possible, cables should be protected with aggregate that does not include particles larger than the No. 8 sieve.

Following are lessons learned concerning additional instrumentation hardware.

a. During continuing pavement construction, the cables for installed probes must be protected with waterproofing and must be protected from construction traffic. In this study, the cables were threaded through PVC

pipes, which was laid out toward the drainage ditch. If construction will include shoulder work, the pipes and any coiled cable must be clearly flagged.

b. To minimize the need for physical maintenance, the use of solar panels is essential. In this study, only the Sentry 200 probes were without solar energy and were entirely dependent on chemical batteries. These probes have already run out of power on two occasions.

c. Protection from electrostatic build-up is critical, especially for long "daisy-chained" dataloggers. In this study, each data logger was grounded with a 2.4-m (8-ft) copper-clad grounding rod. This protection has already saved the instrumentation system at least once.

References

Campbell Scientific, Inc. (1997). "Model 108 Temperature Probe Instruction Manual," Logan, UT.

Campbell Scientific, Inc. (1996). "CS615 Water Content Reflectometer Instruction Manual," Version 8221-07, Logan, UT.

Troxler Electronic Laboratories, Inc., Troxler International, Ltd. (1992). "ProbeReader Plus: Manual of Operation and Instruction," Research Triangle Park, NC.
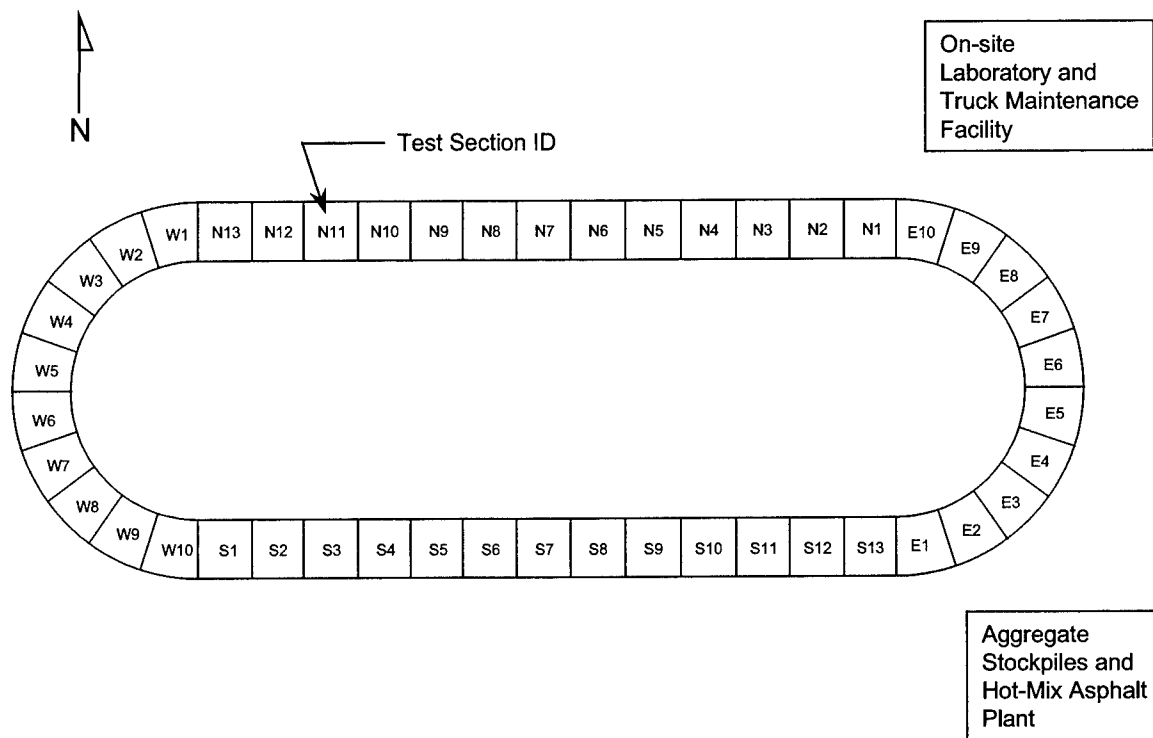
Figure 1. Track layout

Units = m		Units = in.
0.075 to 0.10	Experimental Hot-Mix Asphalt	3 to 4
0.15	Upper Asphalt Binder Course	6
0.23	Lower Asphalt Binder Course	9
0.13	Permeable Asphalt Treated Base	5
0.15	Crushed Granite Base Course	6
0.30	AASHTO A-2 Select Fill	12
	Foundation Soil	

geotextile

Figure 2. Typical pavement cross-section
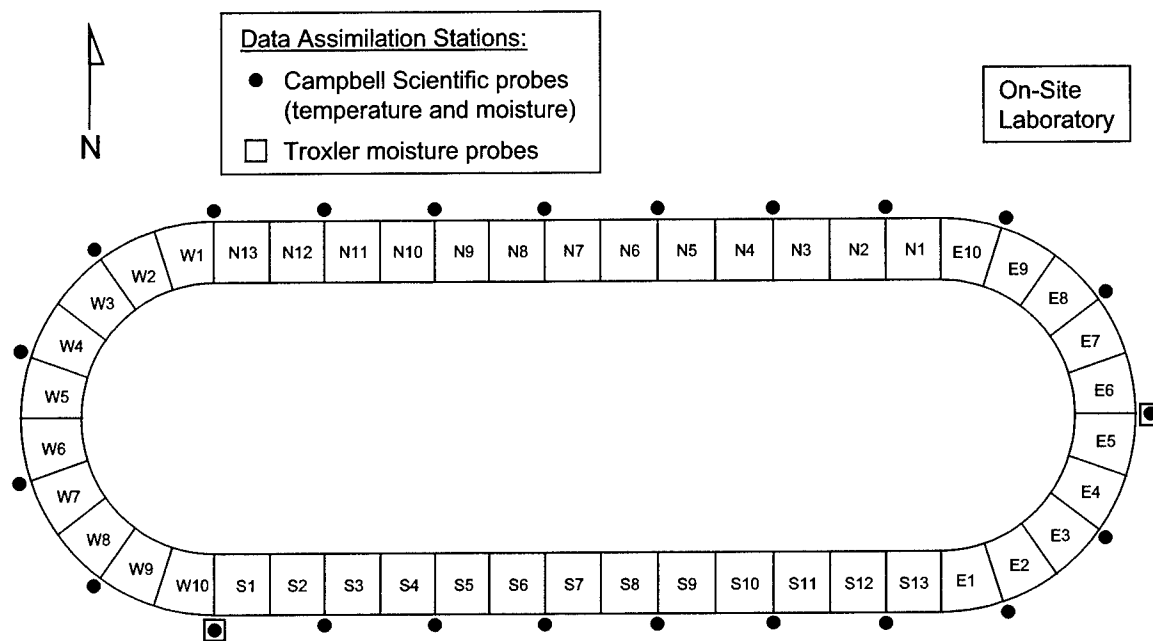
Figure 3. Locations of data assimilation stations
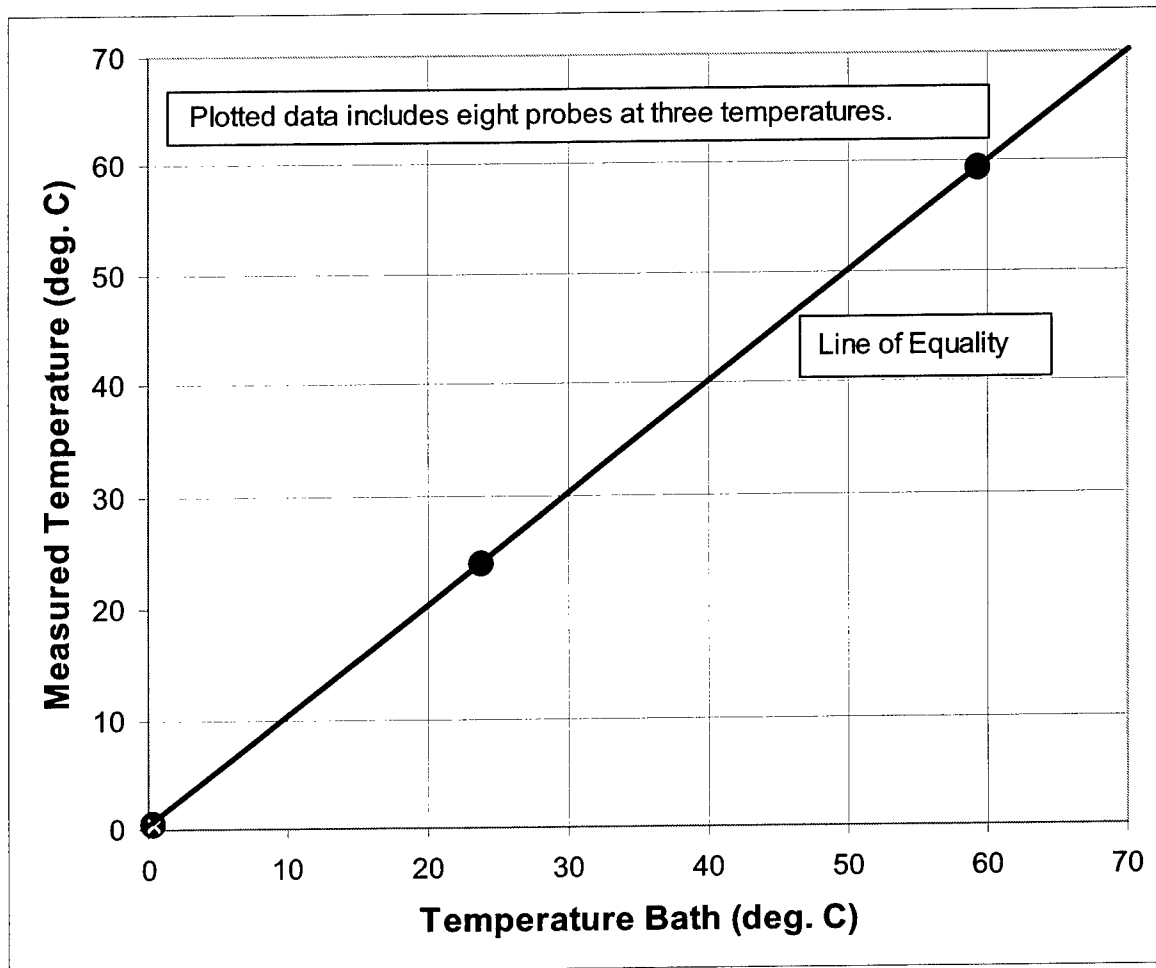
Figure 4. Verification data for Campbell scientific model 108 temperature probes [F = (9/5)*(°C) + 32]
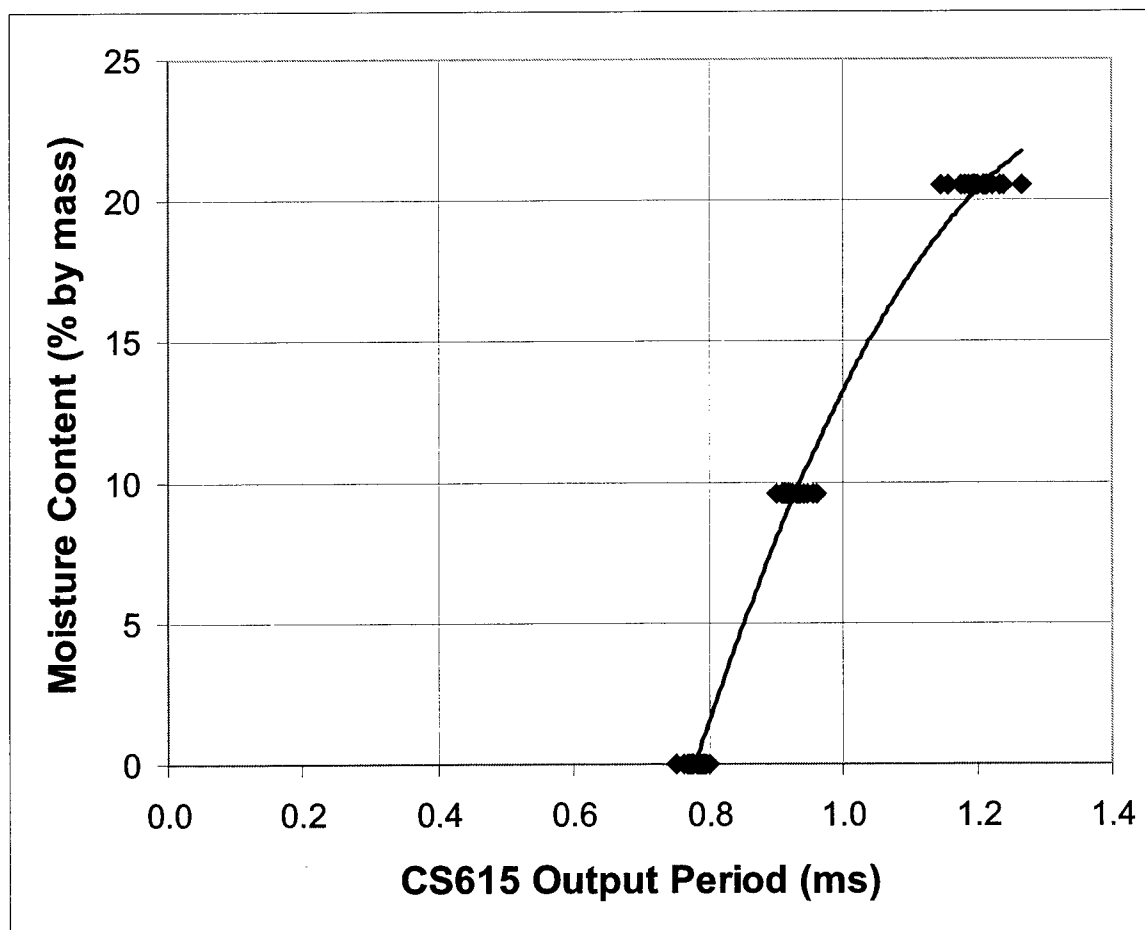
Figure 5.   Calibration data and best-fit composite curve for CS615 moisture probes
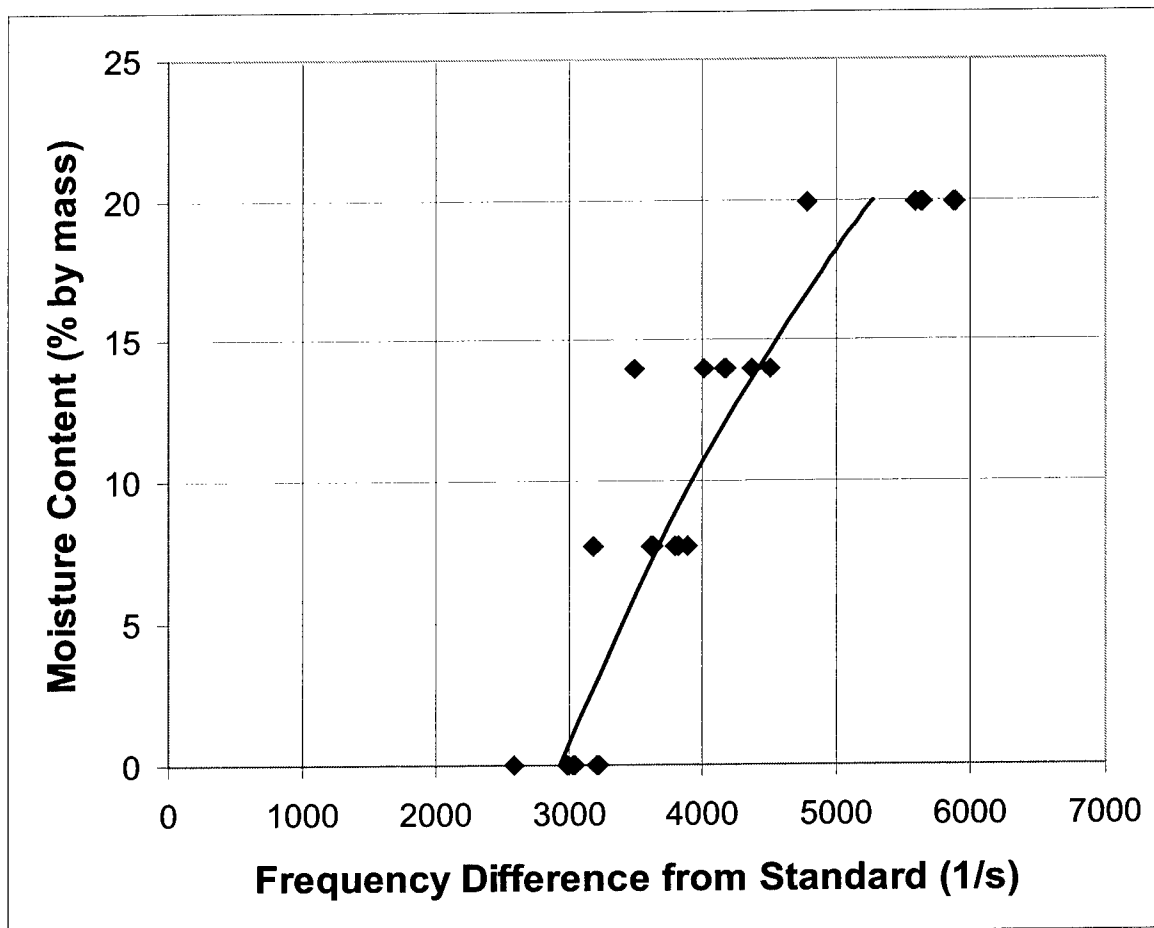
Figure 6.   Calibration data and best-fit composite curve for Troxler moisture probes
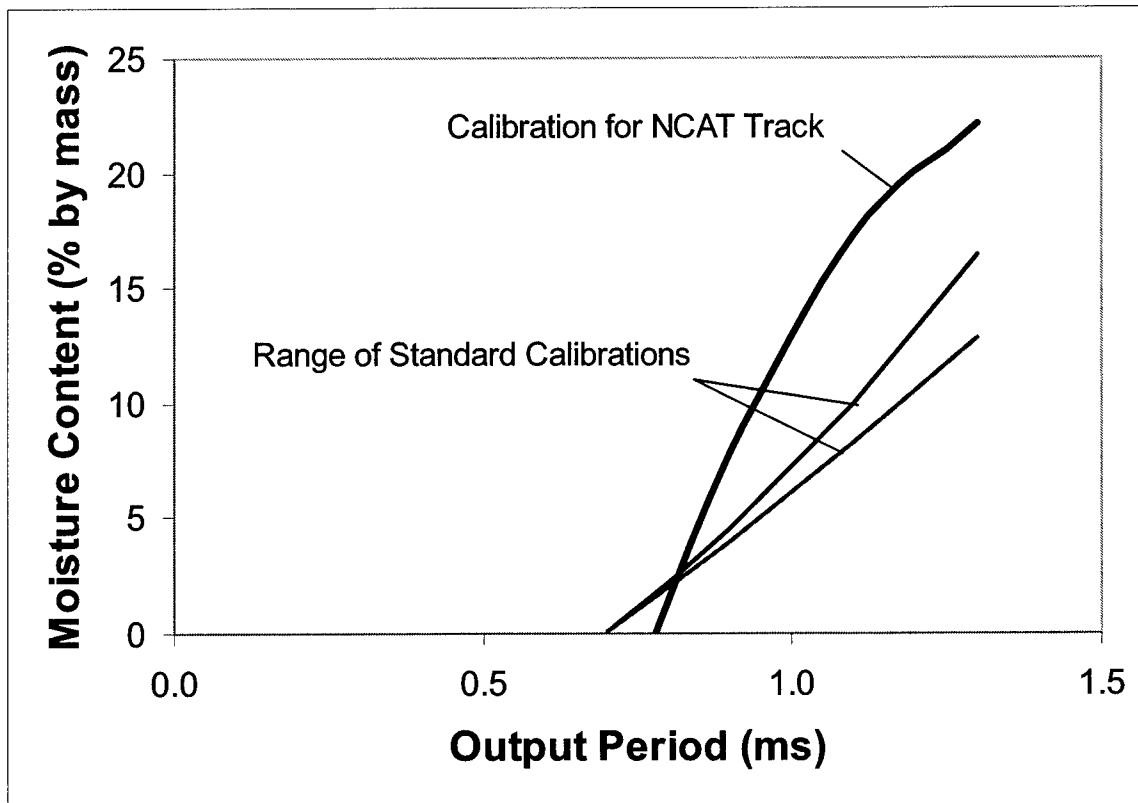
Figure 7. Comparison between the actual calibration and standard calibrations for the CS615 moisture probes
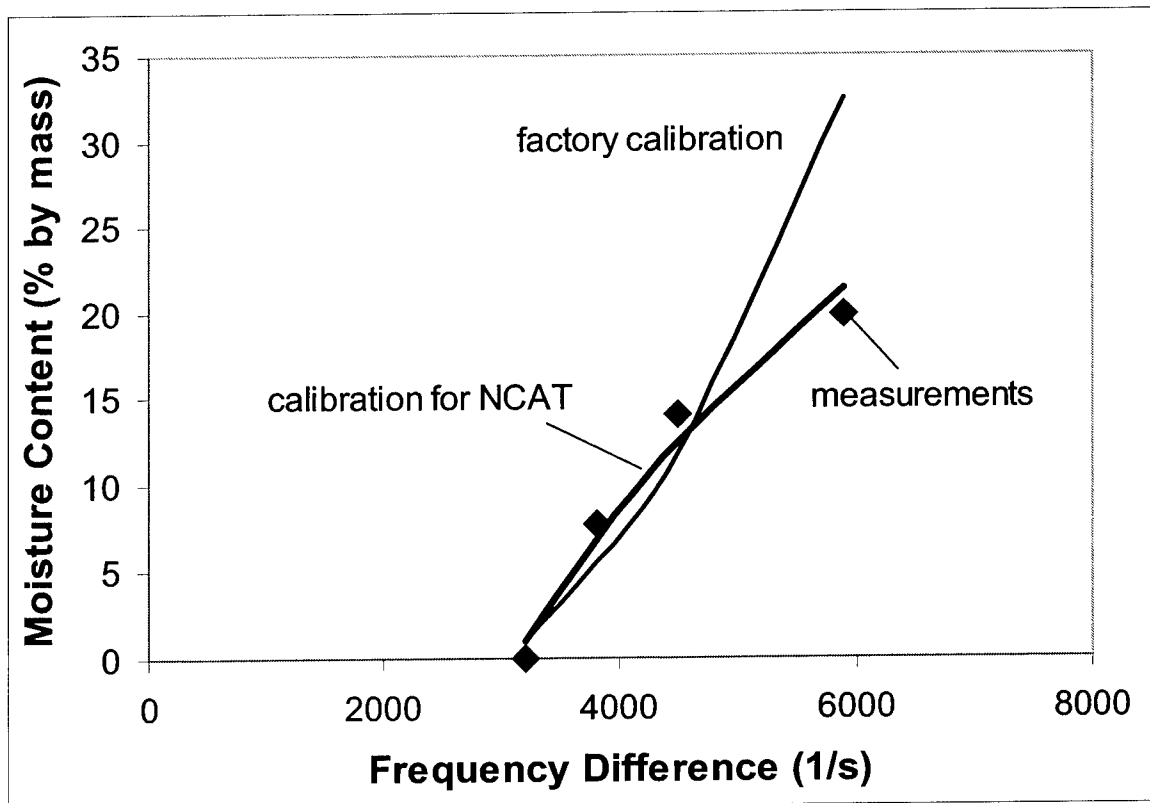
Figure 8. Comparison between the actual calibration and standard calibrations for Troxler probe No. 3
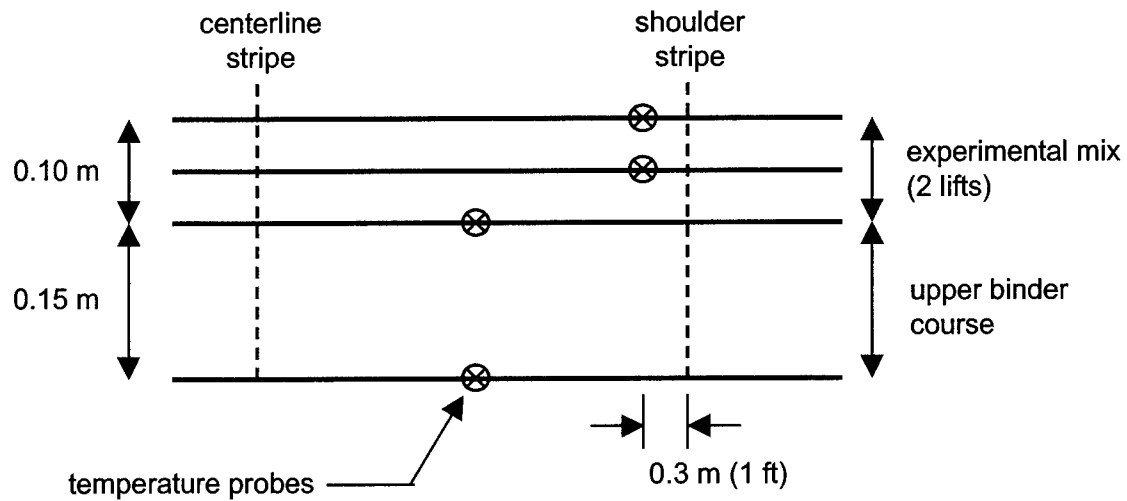
Figure 9. Position of temperature probes in the outside traffic lane
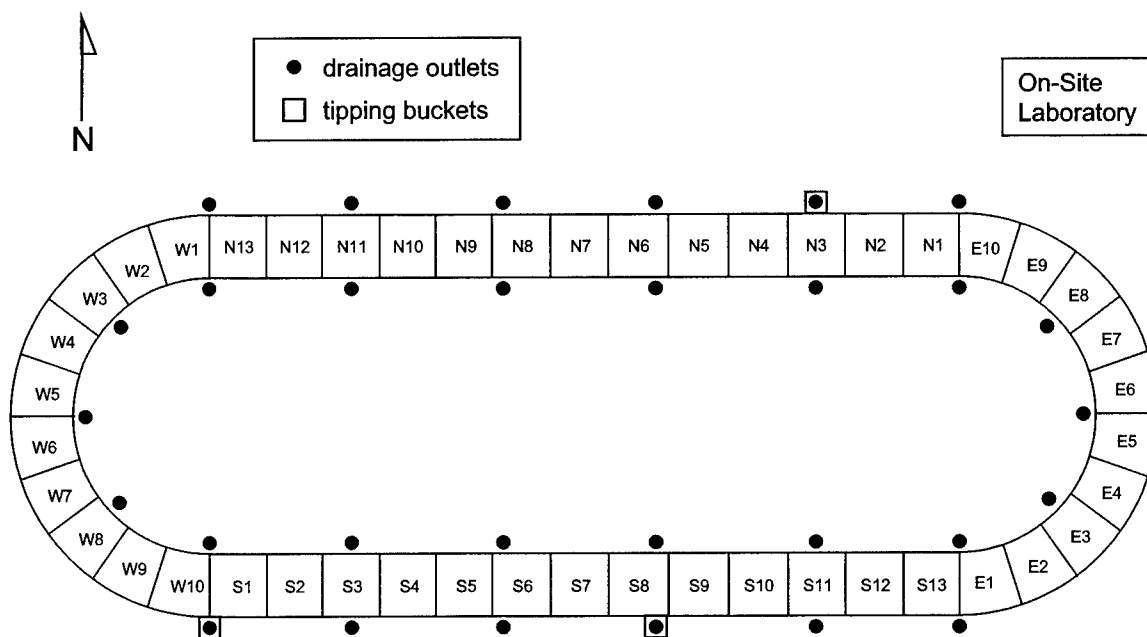
Figure 10. Layout for drainage outlets and tipping buckets
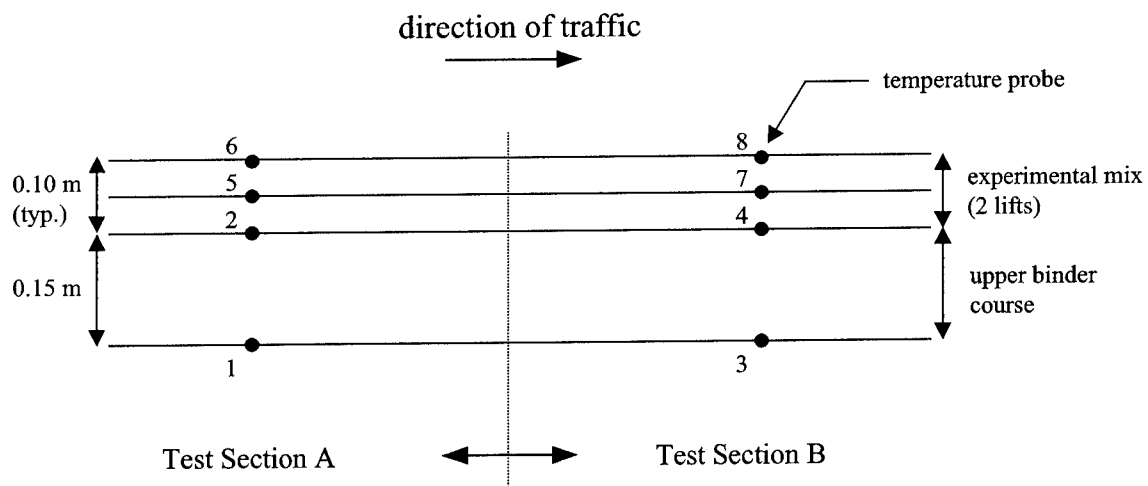
Figure 11. Order of temperature probes as written to data files
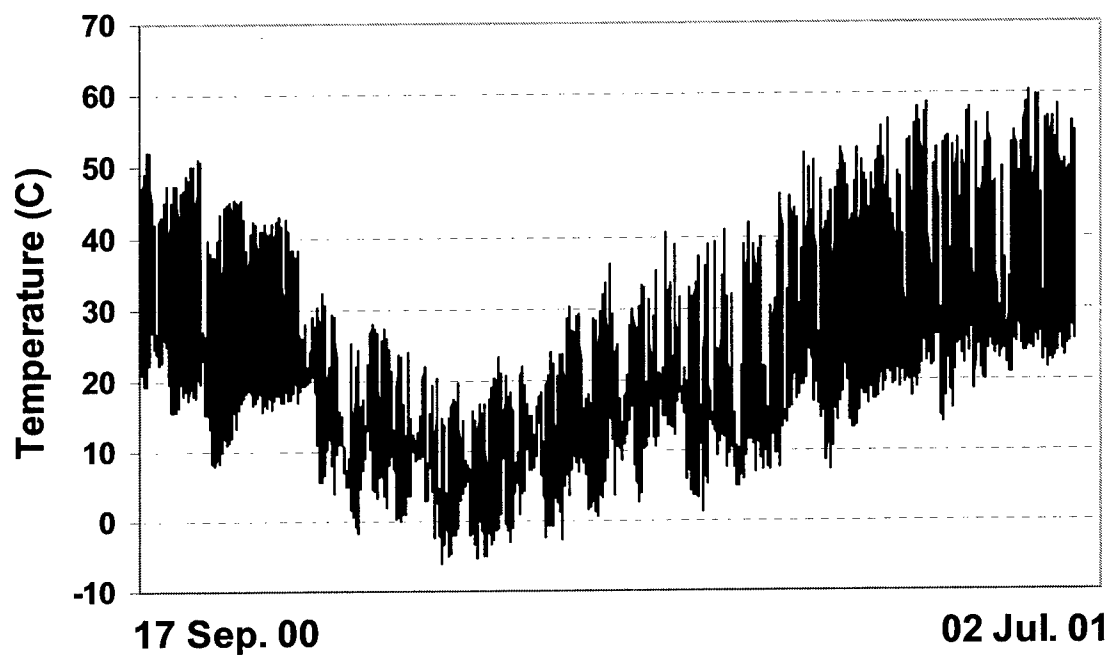
Figure 12. Temperature at pavement surface for test section S1 [F = 9/5(C) + 32]
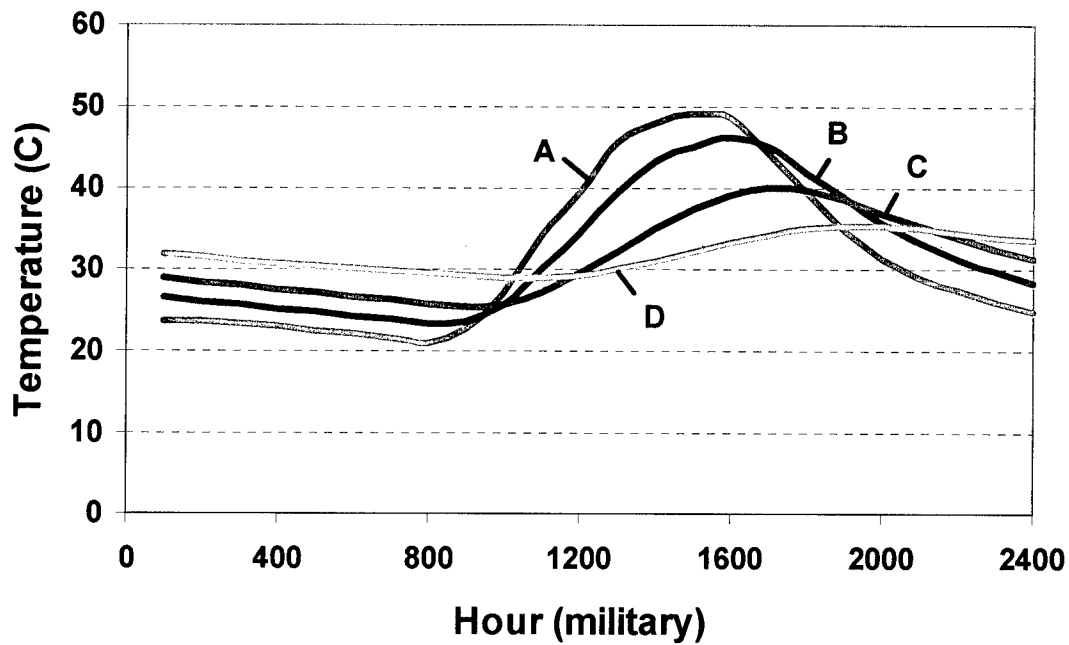
Figure 13. Temperatures for test section S1 during the date 18 September 2000 (for pavement suface ("A"), middle of experimental surface course ("B"), bottom of experimental surface course ("C"), and bottom of upper binder course ("D"))
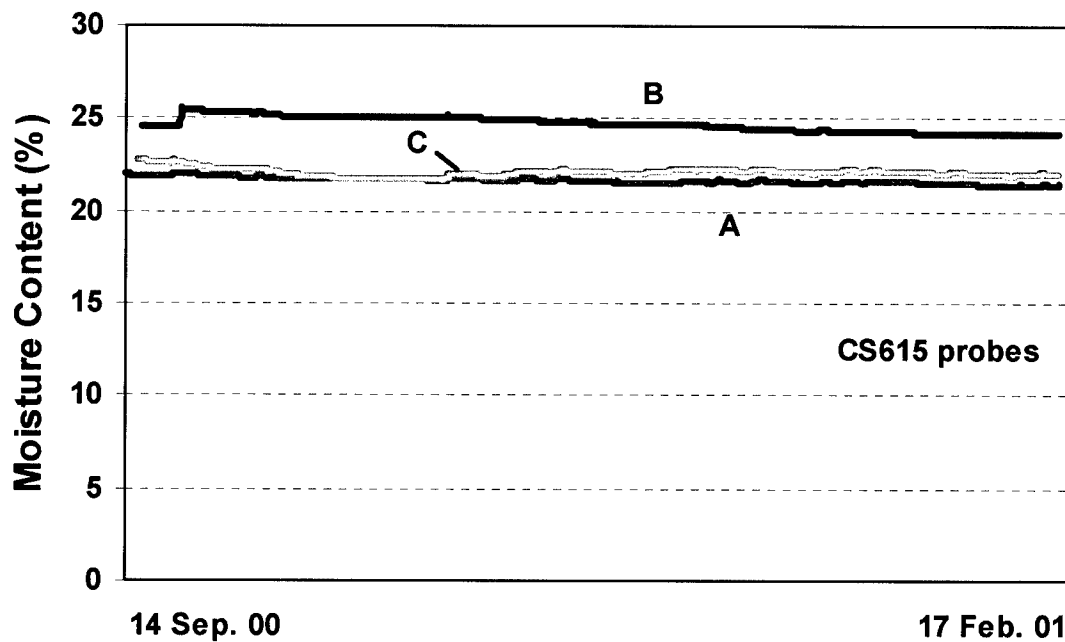
Figure 14. Moisture measurements obtained at the intersection between test sections N3 and N4 ("A"), W10 and S1 ("B"), S8 and S9 ("C")
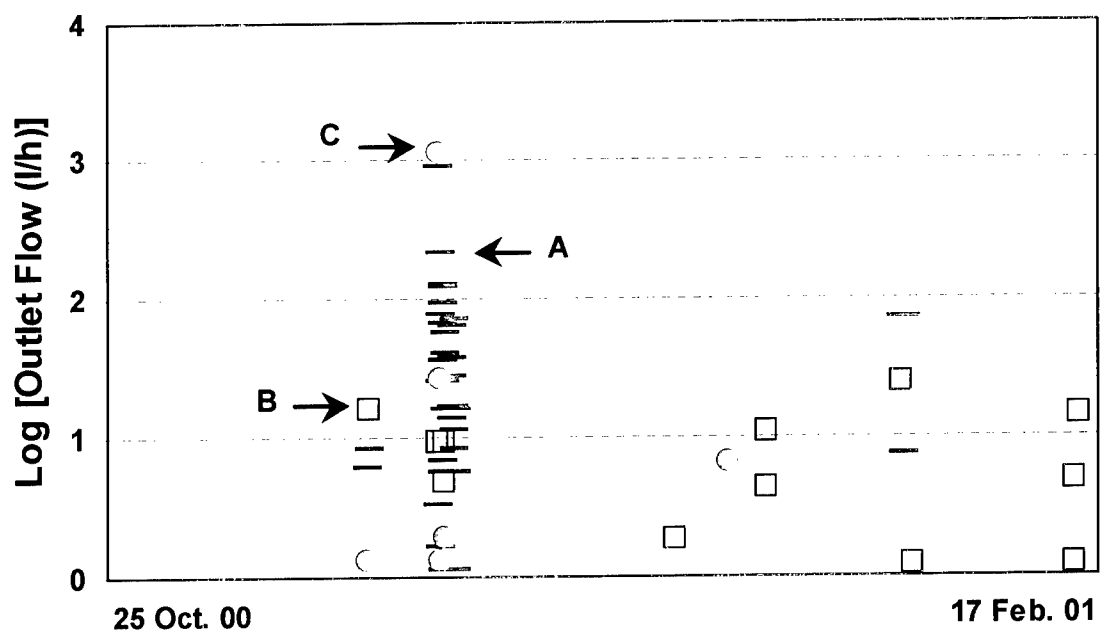
Figure 15. Drainage outlet flow measurements obtained at the intersection between test
sections N3 and N4 ("A"), W10 and S1 ("B"), S8 and S9 ("C")

Table 1
Average Temperatures, °C (°F), Measured by Campbell Scientific Model 108 Probes

Probe No.	Temperature of Immersion Bath °C (°F)		
	0.4444 (32.80)	23.83 (74.90)	59.33 (138.8)
1	0.4406 (32.79)	23.91 (75.04)	59.43 (139.0)
2	0.4189 (32.75)	23.88 (74.99)	59.37 (138.9)
3	0.4537 (32.82)	23.91 (75.04)	59.41 (138.9)
4	0.4319 (32.78)	23.91 (75.04)	59.42 (138.9)
5	0.4145 (32.75)	23.88 (74.98)	59.30 (138.7)
6	0.3971 (32.72)	23.86 (74.94)	59.32 (138.8)
7	0.3840 (32.69)	23.87 (74.97)	59.30 (138.7)
8	0.3756 (32.68)	23.86 (74.96)	59.30 (138.7)

Table 2
Characteristics of the Variability Associated with Model 108 Temperature Probe Verification

Temperature °C (°F)	Percent Variance		Standard Deviation, °C (°F)		
	Between Probes	Between Replicates	Between Probes	Between Replicates	Total
0.44 (32.8)	83	17	0.017 (0.030)	0.038 (0.068)	0.041 (0.074)
23.8 (74.9)	84	16	0.022 (0.040)	0.010 (0.018)	0.024 (0.044)
59.3 (138.8)	86	14	0.056 (0.100)	0.023 (0.041)	0.060 (0.108)

Note: CV = coefficient of variation = (σ/mean)*100 percent.

Table 3
Linear Regression for Average Measured Temperature, as a Function of Both Bath Temperature and Probe

Analysis of Variance					
Model	Sum of Squares	Degrees of Freedom	Mean Square	F-statistic	Significance Level
Regression	32750.4	2	16375.2	5975566	0.000
Residual	0.06029	22	0.00274	N/A	N/A
Total	32750.5	24	N/A	N/A	N/A

Coefficients					
Model	Coefficient Mean[1]	Coefficient Std. Error[1]	Standardized Coeff. Mean	Student's t	Significance Level
Probe No.	0.003854	0.003	-0.001	-1.348	0.191
Bath Temp.	1.002	0.000	1.000	2559.0	0.000

Note: Units used for the analysis were °C. Coefficient of Determination = 1.0.
[1] Unstandardized.

Table 4
Average Period (ms) for Campbell Scientific CS615 Probes During Calibration

Probe No.	Measured Soil Moisture Content (% by mass)		
	0	9.6	20.5
1	0.7529	0.9126	1.147
2	0.7622	0.9218	1.175
3	0.7531	0.9264	1.157
4	0.7745	0.9315	1.214
5	0.7909	0.9379	1.197
6	0.7676	0.9374	1.201
7	0.7928	0.9467	1.224
8	0.7817	0.9490	1.215
9	0.7912	0.9562	1.202
10	0.7738	0.9182	1.181
11	0.7825	0.9242	1.214
12	0.7868	0.9165	1.214
13	0.7825	0.9469	1.211
14	0.7878	0.9617	1.202
15	0.7627	0.9234	1.267
16	0.7846	0.9267	1.240
17	0.7838	0.9238	1.201
18	0.7715	0.9098	1.194
19	0.7904	0.9346	1.212
20	0.7721	0.9024	1.241
21	0.7941	0.9207	1.251
22	0.8001	0.9207	1.240
23	0.7865	0.9236	1.213
24	0.7959	0.9414	1.233
25	0.7843	0.9191	1.202
26	0.7772	0.9219	1.212

Table 5
Calibration Coefficients for Campbell Scientific CS615 Probes

Probe No.	Gravimetric Moisture = $ax^2 + bx + c$ (see note)		
	a	b	c
1	-0.348	1.180	-0.692
2	-0.416	1.301	-0.750
3	-0.202	0.894	-0.558
4	-0.515	1.490	-0.845
5	-0.573	1.644	-0.942
6	-0.350	1.163	-0.686
7	-0.535	1.555	-0.896
8	-0.380	1.232	-0.731
9	-0.338	1.172	-0.716
10	-0.615	1.706	-0.952
11	-0.698	1.869	-1.035
12	-0.876	2.232	-1.214
13	-0.399	1.274	-0.753
14	-0.237	0.967	-0.615
15	-0.556	1.534	-0.847
16	-0.719	1.905	-1.053
17	-0.701	1.884	-1.046
18	-0.736	1.931	-1.052
19	-0.647	1.783	-1.005
20	-0.873	2.199	-1.177
21	-0.892	2.288	-1.255
22	-1.014	2.541	-1.384
23	-0.759	1.999	-1.102
24	-0.656	1.799	-1.017
25	-0.783	2.047	-1.124
26	-0.662	1.787	-0.990
Composite	-0.574	1.618	-0.912

Notes: Gravimetric moisture content is as a decimal. The independent variable (x) is the measured period in milliseconds. Composite parameters were obtained by using average data for all probes for each of the three moisture contents.

Table 6
Characteristics of the Variability Associated with CS615 Probe Calibration

Moisture Content (%)	% Variance Between Probes	% Variance Between Replicates	CV (%) Between Probes	CV (%) Between Replicates	CV (%) Total
0.0	44	56	1.4	1.5	2.1
9.6	31	69	1.2	1.8	2.1
20.5	21	79	1.3	2.6	2.9
Note: CV = coefficient of variation = $(\sigma/\text{mean})*100$ percent.					

Table 7
Average Frequency (1/s) for Troxler Sentry 200 Probes During Calibration

Probe No.	Measured Soil Moisture Content (% by mass)			
	0	7.7	14.0	19.9
3	3207	3821	4503	5884
4	3046	3624	4165	5623
5	3035	3783	4169	5591
6	3231	3878	4366	5877
7	2995	3606	4011	5644
8	2599	3190	3490	4780

Table 8
Calibration Coefficients for Troxler Sentry 200 Probes

Probe No.	Gravimetric Moisture = $(1/C1)\ln[(x-C2)/C0]$ (see note)		
	C0	C1	C2
3	3114	0.0298	0
4	2946	0.0296	0
5	2990	0.0291	0
6	3142	0.0287	0
7	2893	0.0300	0
8	2542	0.0288	0
Composite	2931	0.0293	0

Notes: Gravimetric moisture content is as a percent. The independent variable (x) is the measured frequency difference (1/s), relative to a standard. Composite parameters were obtained by using average data for all probes for each of three moisture contents.

Table 9
Characteristics of the Variability Associated with Troxler Probe Calibration

Moisture Content (%)	% Variance Between Probes	% Variance Between Replicates	CV (%) Between Probes	CV (%) Between Replicates	CV (%) Total
0.0	> 99	< 1	7.5	0.02	7.5
7.7	> 99	< 1	6.9	0.05	6.9
14	> 99	< 1	8.6	0.02	8.6
19.9	> 99	< 1	7.3	0.02	7.3
Note: CV = coefficient of variation = $(\sigma/\text{mean})*100$ percent.					

Table 10
Installation Data for Campbell Scientific CS615 Probes

Test Section	Probe No.	Average Reading (ms)	Moisture Contents (% by mass)		
			(1)	(2)	(3)
N1_N2	26	0.8962	7.7	10.7	3
N3_N4	2	0.8954	7.7	9.6	1.9
N5_N6	3	0.8653	5.9	9.2	3.3
N7_N8	4	0.8887	7.3	10.7	3.4
N9_N10	5	0.9098	8.5	10.8	2.3
N11_N12	6	0.8345	3.9	7.6	3.7
N13_W1	7	0.8456	4.6	6.7	2.1
W2_W3	8	0.8629	5.7	no data	no data
W4_W5	9	0.8481	4.8	6.2	1.4
W6_W7	10	0.8083	2.1	4.8	2.7
W8_W9	11	0.8373	4.1	no data	no data
W10_S1	12	0.8941	7.6	11.6	4
S2_S3	13	0.8845	7.0	10.7	3.7
S4_S5	14	0.8919	7.5	9.7	2.2
S6_S7	15	0.8520	5.0	9.8	4.8
S8_S9	16	0.8512	5.0	6.9	1.9
S10_S11	18	0.8305	3.6	8.5	4.9
S12_S13	19	0.8681	6.0	10.1	4.1
E1_E2	20	0.8697	6.1	12.5	6.4
E3_E4	21	0.8498	4.9	7.1	2.2
E5_E6	22	0.8735	6.4	8.7	2.3
E7_E8	23	0.8551	5.2	6.9	1.7
E9_E10	25	0.9101	8.5	7.9	-0.6
Average			5.9	8.9	2.9

(1) Estimated by probe after installation using the composite calibration parameters, which were produced with all probe data combined.
(2) Measured oven-dry moisture of scalped select fill used to cover probe.
(3) Measured oven-dry moisture (2) minus that estimated by probe (1).
Note: All probes were installed at the center of the outer traffic lane.

Table 11
Installation Data for Troxler Sentry 200 Probes

Test Section	Probe No.	Average Reading (1/s)	Moisture Contents (% by mass)		
			(1)	(2)	(3)
W10_S1	3	4761	14.2	11.6	-2.6
	4	4153	11.6		0.0
	5	4374	13.1		-1.5
E5_E6	6	4434	12.0	8.7	-3.3
	7	4224	12.6		-3.9
	8	3658	12.6		-3.9
Average			12.7	10.2	-2.5

(1) Estimated by probe after installation using the calibration parameters that were developed for each individual probe.
(2) Measured oven-dry moisture of scalped select fill used to cover probe.
(3) Measured oven-dry moisture (2) minus that estimated by probe (1).
Note: Probes 3 and 6 were installed at intersection between the outer traffic lane and the shoulder. All other probes were installed at the center of the outer traffic lane.

Table 12
Final Adjusted Moisture Content Estimates at the Time of Installing Campbell Scientific CS615 Probes

Test Section	Probe No.	Average Reading (ms)	Moisture Content (% by mass)
N1_N2	26	0.8962	10.6
N3_N4	2	0.8954	10.6
N5_N6	3	0.8653	8.7
N7_N8	4	0.8887	10.2
N9_N10	5	0.9098	11.4
N11_N12	6	0.8345	6.7
N13_W1	7	0.8456	7.5
W2_W3	8	0.8629	8.6
W4_W5	9	0.8481	7.6
W6_W7	10	0.8083	5.0
W8_W9	11	0.8373	6.9
W10_S1	12	0.8941	10.5
S2_S3	13	0.8845	9.9
S4_S5	14	0.8919	10.3
S6_S7	15	0.8520	7.9
S8_S9	16	0.8512	7.8
S10_S11	18	0.8305	6.5
S12_S13	19	0.8681	8.9
E1_E2	20	0.8697	9.0
E3_E4	21	0.8498	7.7
E5_E6	22	0.8735	9.2
E7_E8	23	0.8551	8.1
E9_E10	25	0.9101	11.4
Average			8.7
Standard Deviation			1.69

Notes:
(1) The final adjusted equation for estimating moisture content is:
$$y = -0.574x^2 + 1.618x - 0.883, \text{ where}$$
y = moisture content as a decimal and
x = measured period (ms)
(2) All probes were installed at the center of the outer traffic lane.

Table 13
Final Adjusted Calibration Coefficients for Troxler Sentry 200 Probes

Test Section	Probe No.	Gravimetric Moisture = $(1/C1)\ln[(x-C2)/C0]$ (see note)		
		C0	C1	C2
W10_S1	3	3355	0.0298	0
	4	3172	0.0296	0
	5	3216	0.0291	0
E5_E6	6	3376	0.0287	0
	7	3118	0.0300	0
	8	2732	0.0288	0

Notes: Gravimetric moisture content is as a percent. The independent variable (x) is the measured frequency difference (1/s). C0 required adjustment, while C1 and C2 remained unchanged.

Table 14
Final Adjusted Moisture Content Estimates at the Time of Installing Troxler Sentry 200 Probes

Station	Probe No.	Average Reading (1/s)	Moisture Content (% by mass)
W10_S1	3	4761	11.7
	4	4153	9.1
	5	4374	10.6
E5_E6	6	4434	9.5
	7	4224	10.1
	8	3658	10.1
Average			10.2
Standard Deviation			0.92

Note: Probes 3 and 6 were installed at intersection between the outer traffic lane and the shoulder. All other probes were installed at the center of the outer traffic lane.

Table 15
Moisture Measurements Obtained by the CS615 Probes and Collected Using a Hand-Held Keyboard

Test Section	Moisture Content (% by mass)				
	15 Nov. 1999	28 Feb. 2000	22 Mar. 2000	21 Aug. 2000	30 Aug. 2000
N1_N2	10.6	21.3	21.3	20.9	20.9
N3_N4	10.6	22.2	22.1	22.1	22.0
N5_N6	8.7	20.7	20.7	21.2	21.2
N7_N8	10.2	22.0	22.0	22.3	22.3
N9_N10	11.4	22.7	22.7	23.2	23.1
N11_N12	6.7	22.4	22.3	22.5	22.5
N13_W1	7.5	22.4	22.0	21.9	21.9
W2_W3	8.6	22.0	19.8	19.4	19.5
W4_W5	7.6	23.0	23.2	24.9	24.5
W6_W7	5.0	22.5	22.6	23.1	23.1
W8_W9	6.9	22.3	22.4	24.8	24.9
W10_S1	10.5	24.8	24.9	24.8	24.8
S2_S3	9.9	24.4	24.6	24.8	no data
S4_S5	10.3	23.3	23.3	25.6	no data
S6_S7	7.9	22.9	23.0	24.9	no data
S8_S9	7.8	21.4	21.4	23.8	23.6
S10_S11	6.5	22.6	22.7	23.8	23.7
S12_S13	8.9	23.4	23.5	23.6	23.6
E1_E2	9.0	23.9	24.3	25.4	25.4
E3_E4	7.7	23.2	23.5	24.9	no data
E5_E6	9.2	21.8	21.8	21.3	21.3
E7_E8	8.1	22.3	22.2	21.9	21.8
E9_E10	11.4	24.3	24.4	24.8	no data
Average	8.7	22.7	22.6	23.3	22.8
Standard Deviation	1.69	1.02	1.24	1.69	1.58

Note: All probes were installed at the center of the outer traffic lane.

Table 16
Moisture Measurements Obtained by the Sentry 200 Probes and
Collected Using a Hand-Held Data Acquisition Computer

Station	Moisture Content (% by mass)			
	15 Nov. 1999	22 Mar. 2000	17 Sep. 2000	18 Feb. 2001
W10_S1	11.7	21.8	22.5	20.7
	9.1	20.8	21.0	20.2
	10.6	21.9	22.2	20.9
E5_E6	9.5	20.6	20.1	21.0
	10.1	20.2	no data*	20.9
	10.1	21.4	no data*	21.6
Average	10.2	21.1	21.5	20.9
Standard Deviation	0.92	0.69	1.12	0.47

Note: Probes 3 and 6 were installed at intersection between the outer traffic lane and the shoulder. All other probes were installed at the center of the outer traffic lane.
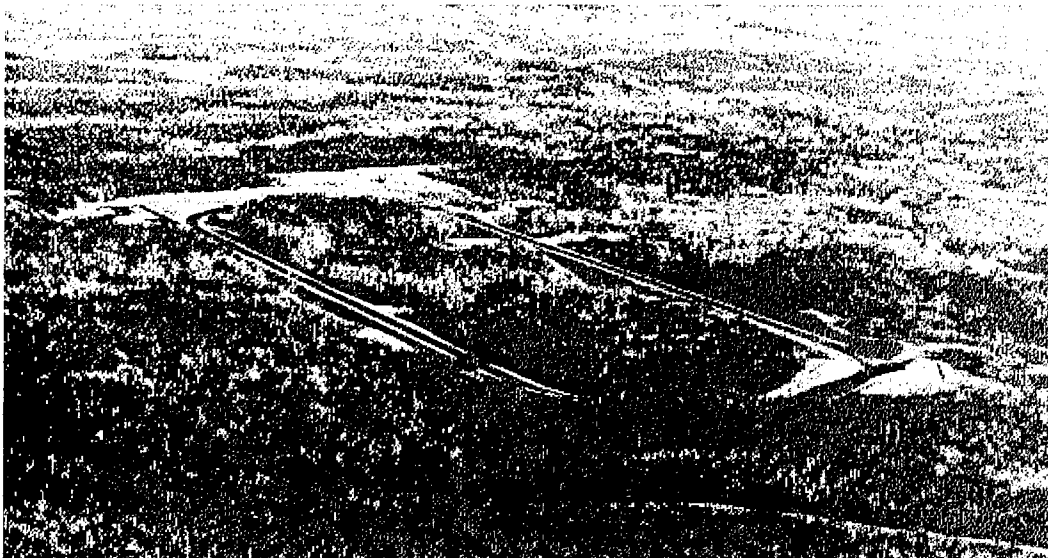* Caused by low batteries
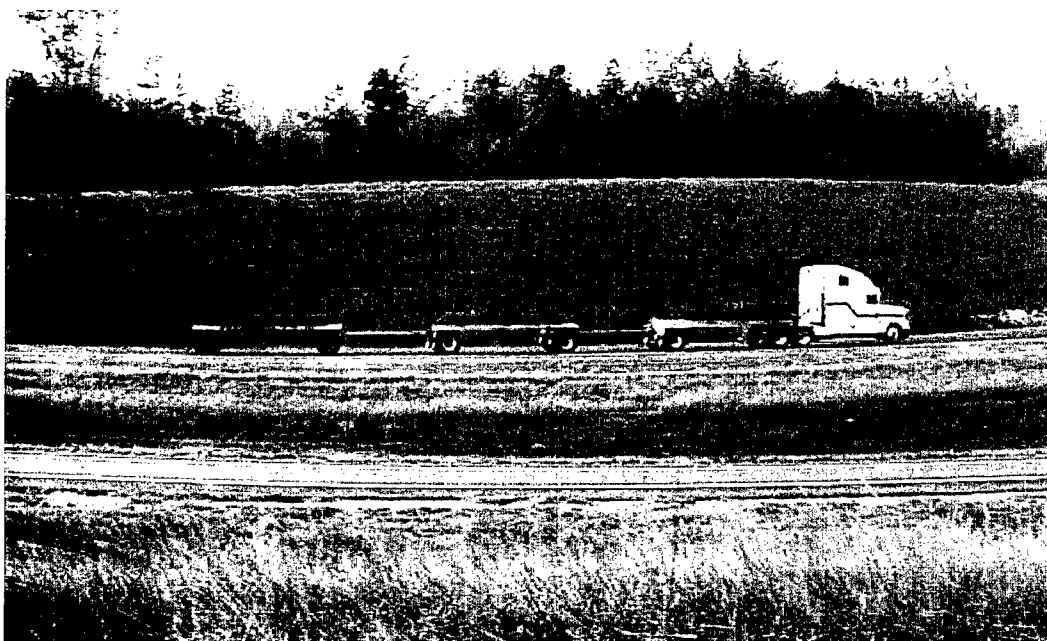
Photo 1. Aerial view of the NCAT test track

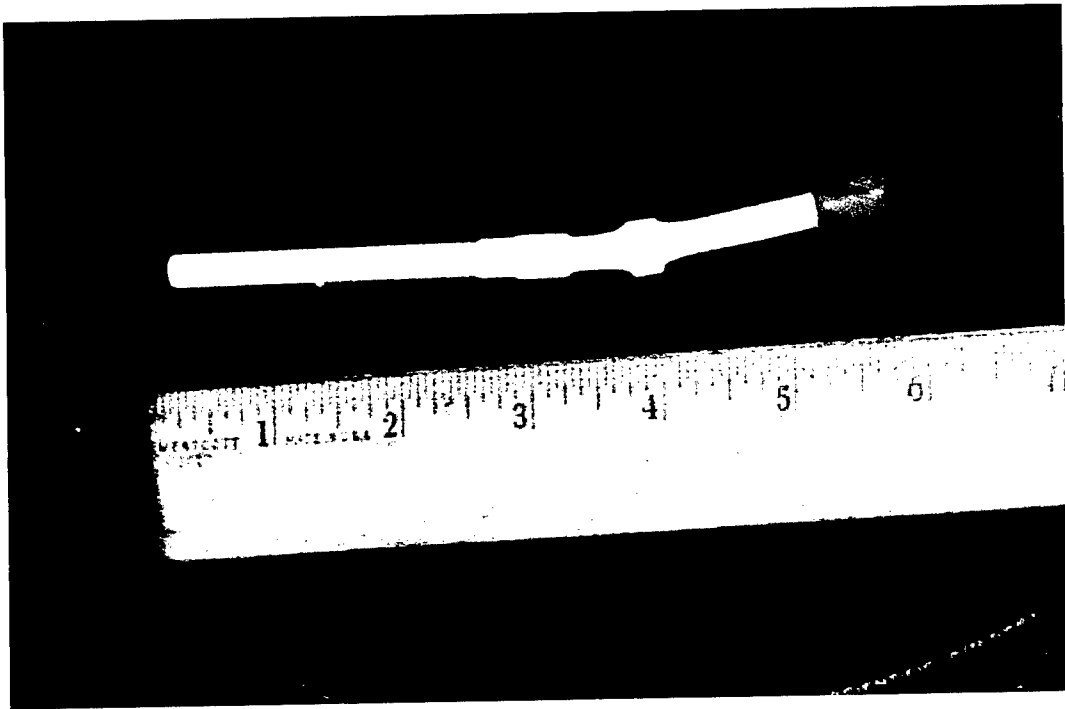Photo 2. Manually-driven triple-trailer truck

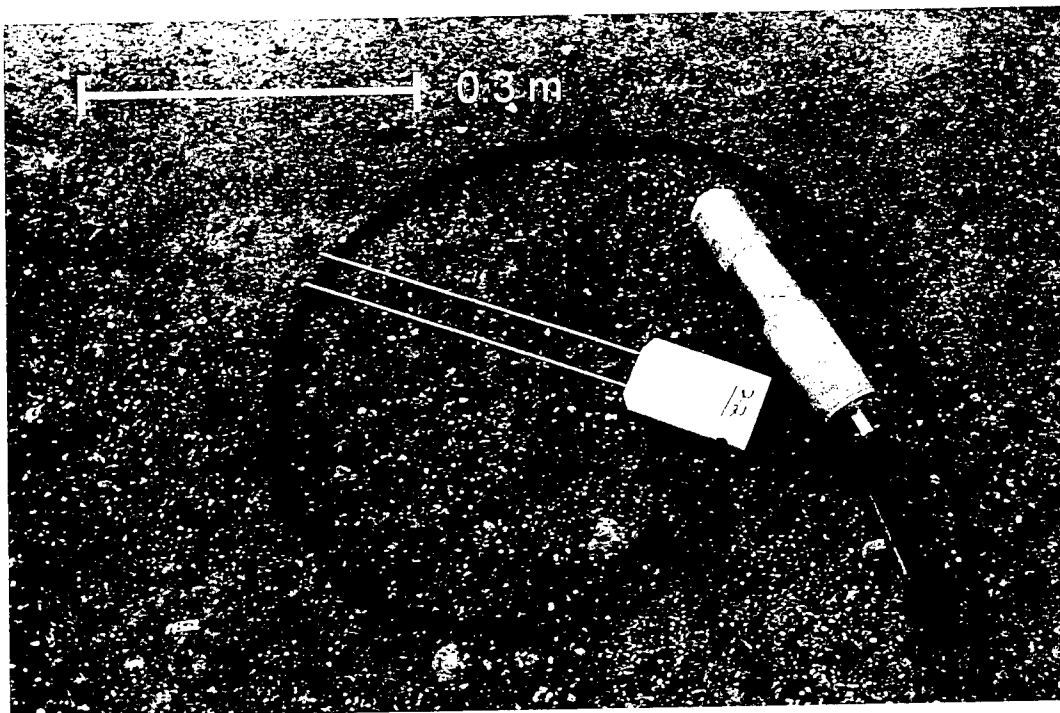Photo 3. Temperature probe, Campbell Scientific Model 108

Photo 4. Soil moisture probes, CS615 on left and Sentry 200 on right

Photo 5.   Weather-proof enclosures: Campbell Scientific at top and Troxler at
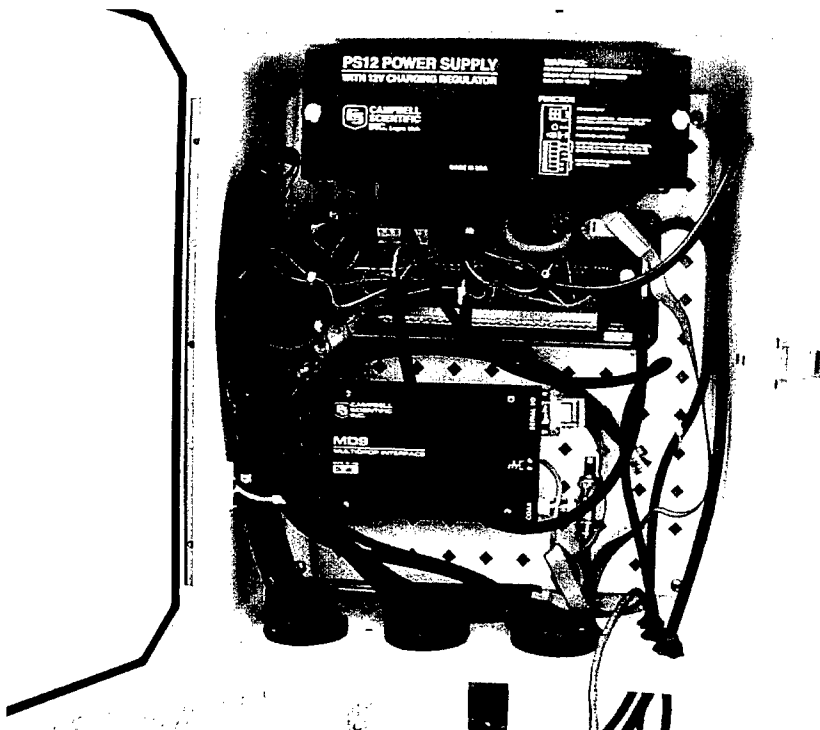   bottom

Photo 6. View inside the Campbell Scientific enclosure
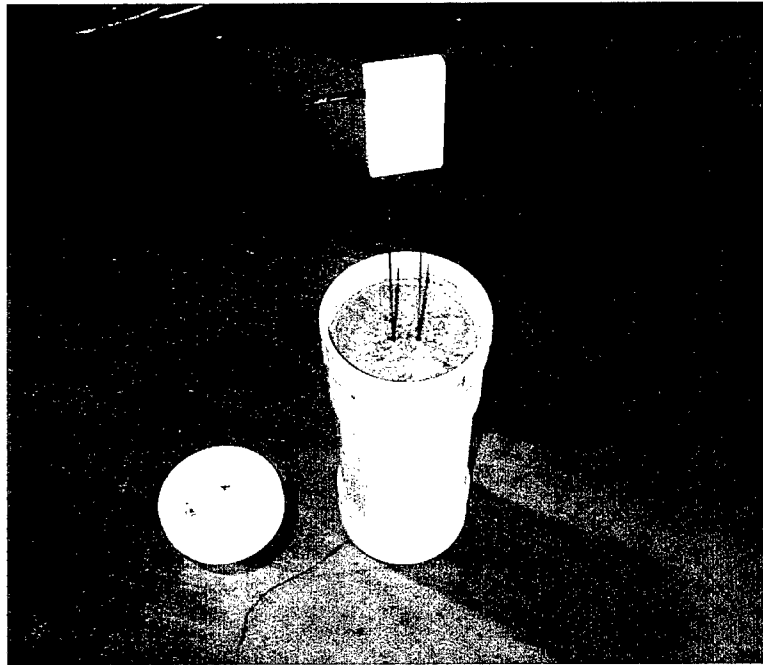
Photo 7. View inside the Troxler enclosure

Photo 8. Calibration of the CS615 moisture probes
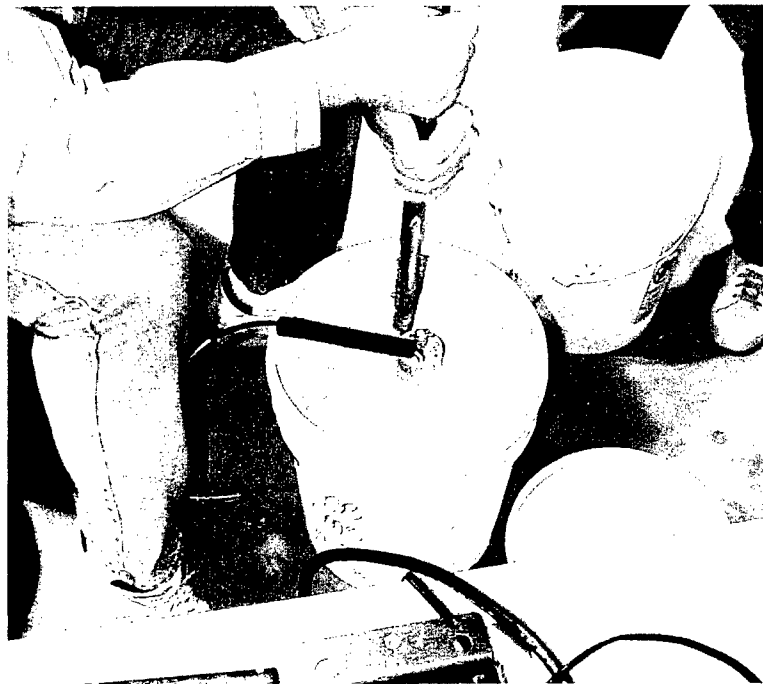

Photo 9. Calibration of the Sentry 200 moisture probes

Photo 10. Trench for installing a CS615 moisture probe

Photo 11. Trench for installing 2 Sentry 200 moisture probes, along with a CS615 moisture probe
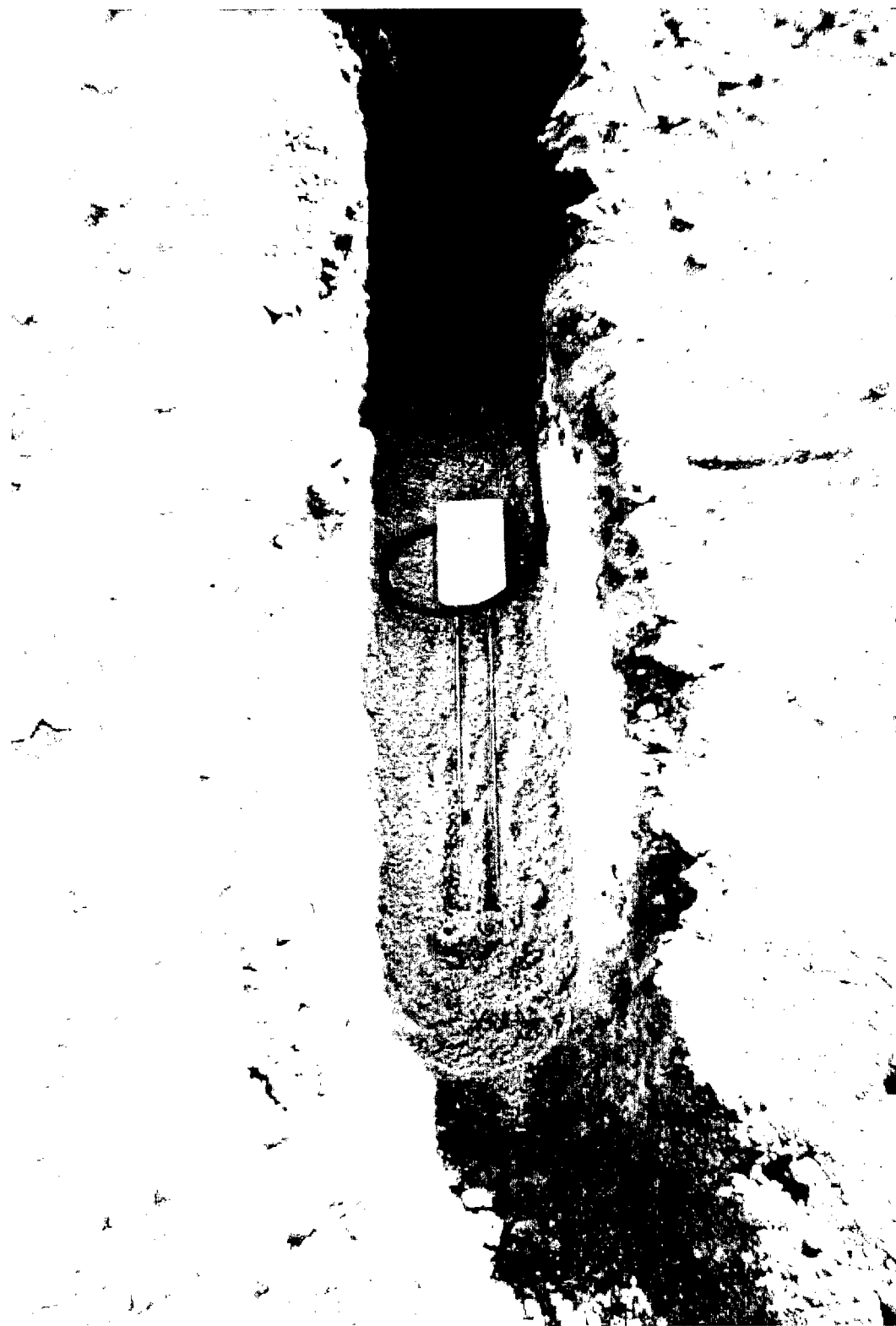
Photo 12. CS615 probe in-place and ready for burial
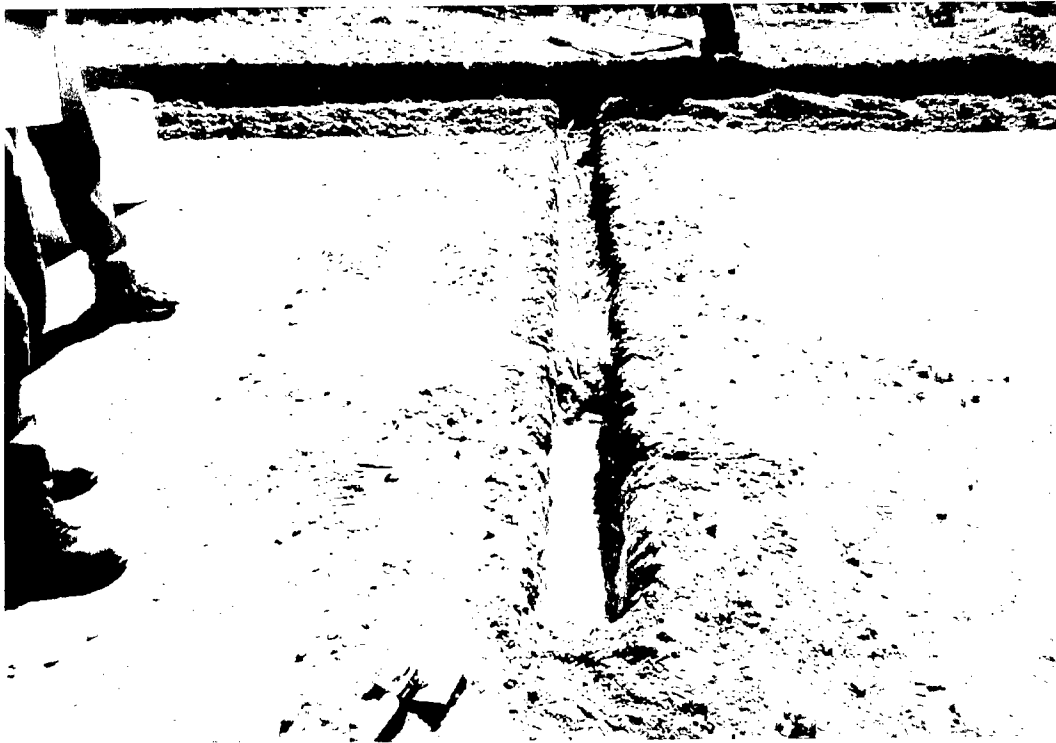
Photo 13. CS615 probe installation after compacting select fill

Photo 14. Completed moisture probe installation

Photo 15. Moisture probe cable threaded through PVC pipe, extending through pavement shoulder

Photo 16. Compacting ropes into asphalt concrete to form temperature probe trenches
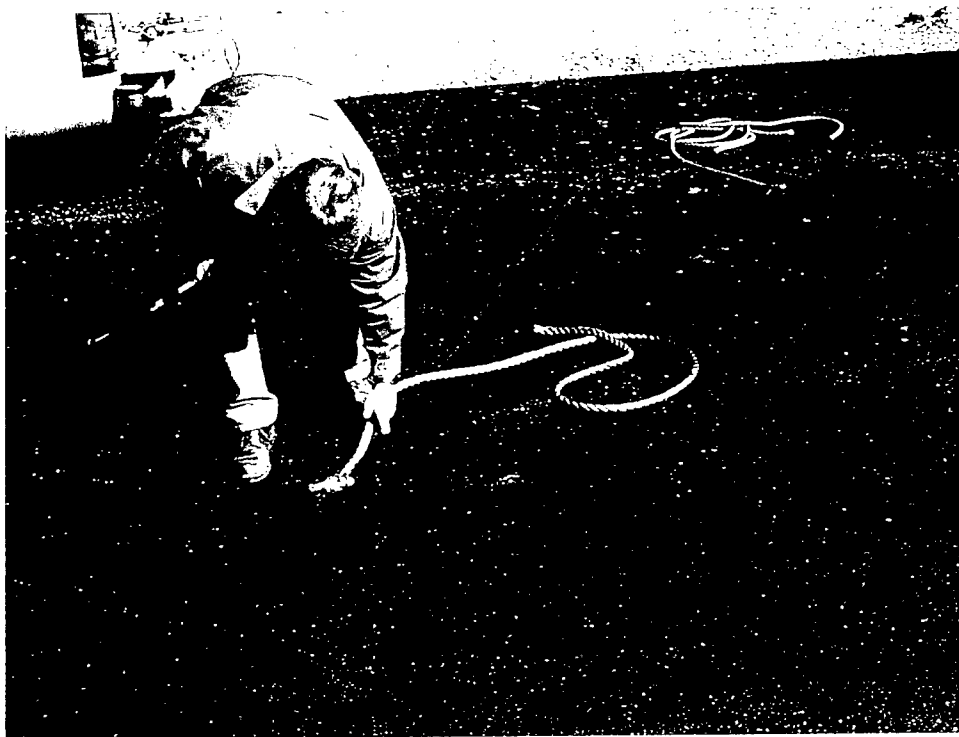
Photo 17. Well-formed trench
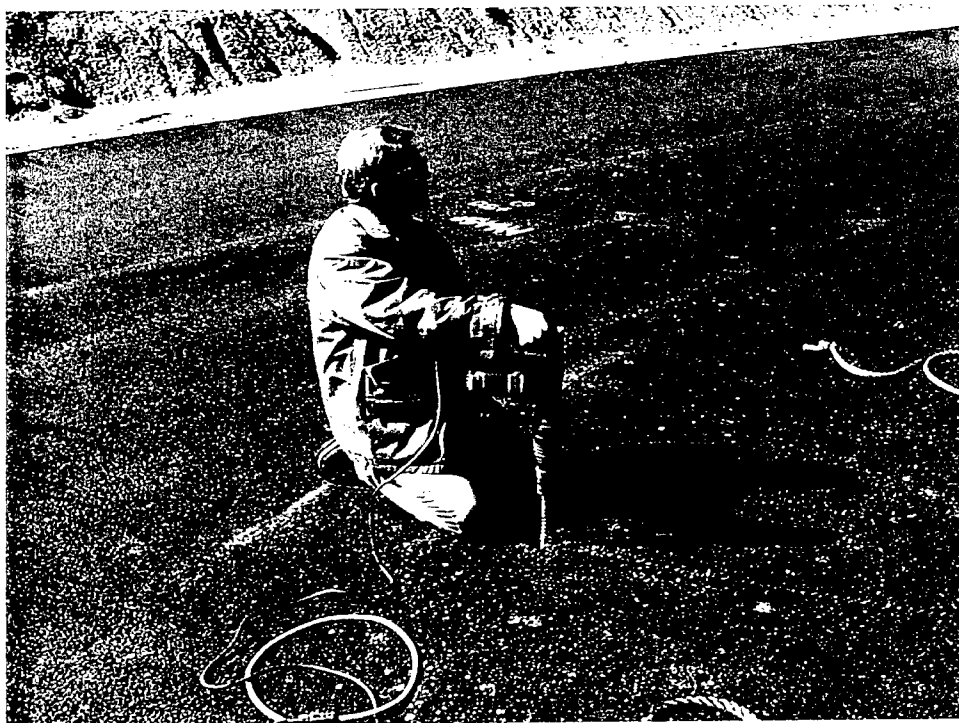
Photo 18. Drilling down to bottom of upper binder course

Photo 19.   Two thermistors in-position: one vertical in hole and one horizontal

Photo 20. Thermistor protected with fine aggregate

Photo 21. Pouring polymer-modified binder into probe trench

Photo 22. Trench on top of upper binder course, covered with fine aggregate

Photo 23.   Completed temperature probe installation on top of the upper binder course

Photo 24.   Stepping on a metal plate to compact hot-mix over the probe at the pavement surface

Photo 25. Darker fine aggregate for use at the pavement surface

Photo 26. Weather station

Photo 27. Tipping bucket

Photo 28. Doghouse enclosure for a tipping bucket

Photo 29. Water flow from drainage system

Appendix A
Statistical Analyses

Table A1

Analysis of Variance for Campbell Scientific Model 108 Temperature Probes at Verification Temperature of 0.44°C (32.8°F)

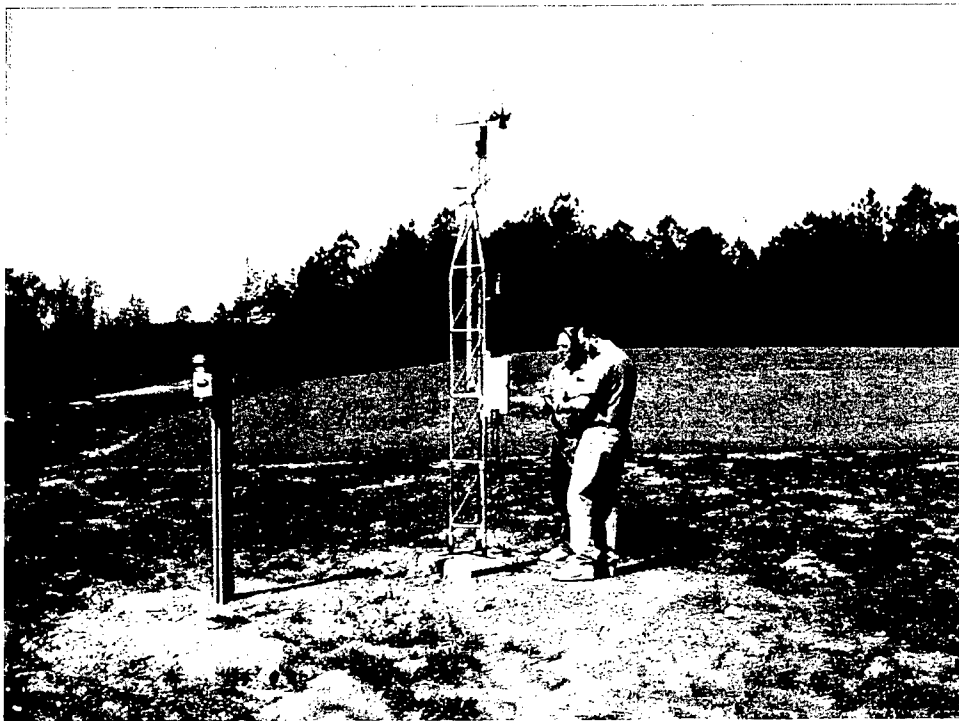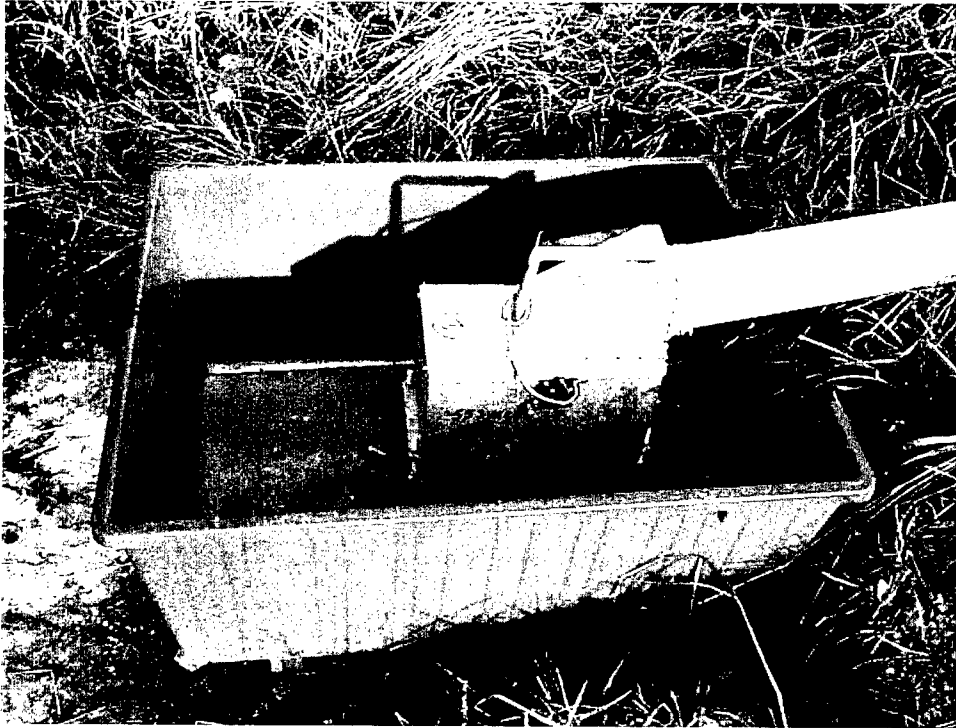| Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 7	0.01585	0.002264	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 16	0.07411	0.001430	σ_w^2
Total	pr − 1 = 23	0.08996	NA	NA

Note: Units used for the analysis were °C.
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A2

Analysis of Variance for Campbell Scientific Model 108 Temperature Probes at Verification Temperature of 23.8°C (74.9°F)

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 7	0.01108	0.001583	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 16	0.001549	0.00009683	σ_w^2
Total	pr − 1 = 23	0.01263	NA	NA

Note: Units used for the analysis were °C.
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A3

Analysis of Variance for Campbell Scientific Model 108 Temperature Probes at Verification Temperature of 59.3°C (138.8°F)

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 7	0.06843	0.009776	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 16	0.008235	0.0005147	σ_w^2
Total	pr − 1 = 23	0.07667	NA	NA

Note: Units used for the analysis were °C.
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A4

Analysis of Variance for CS615 Calibration Data at Calibration Moisture Content of 0.0 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 25	0.01209	0.0004836	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 52	0.00741	0.0001424	σ_w^2
Total	pr − 1 = 77	0.01950	NA	NA

Note: Units used for the analysis were output period (ms).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A5
Analysis of Variance for CS615 Calibration Data at Calibration Moisture Content of 9.6 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 25	0.01577	0.0006310	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 52	0.01392	0.0002677	σ_w^2
Total	pr − 1 = 77	0.02969	NA	NA

Note: Units used for the analysis were output period (ms).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A6
Analysis of Variance for CS615 Calibration Data at Calibration Moisture Content of 20.5 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 25	0.04316	0.0017270	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 52	0.04942	0.0009503	σ_w^2
Total	pr − 1 = 77	0.09258	NA	NA

Note: Units used for the analysis were output period (ms).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A7
Analysis of Variance for Troxler Calibration Data at Calibration Moisture Content of 0.0 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 5	774221	154844	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 12	4.0	0.33	σ_w^2
Total	pr − 1 = 17	774225	NA	NA

Note: Units used for the analysis were frequency difference (1/s).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A8
Analysis of Variance for Troxler Calibration Data at Calibration Moisture Content of 7.7 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 5	940072	188014	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 12	48	4.0	σ_w^2
Total	pr − 1 = 17	940120	NA	NA

Note: Units used for the analysis were frequency difference (1/s).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A9

Analysis of Variance for Troxler Calibration Data at Calibration Moisture Content of 14.0 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 5	1860944	372189	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 12	11	0.89	σ_w^2
Total	pr – 1 = 17	1860955	NA	NA

Note: Units used for the analysis were frequency difference (1/s).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

Table A10

Analysis of Variance for Troxler Calibration Data at Calibration Moisture Content of 19.9 percent

Source of Variability	Degrees of Freedom[1]	Sum of Squares	Mean Square	Expected Mean Square[2]
Between Probes	p-1 = 5	2475382	495076	$\sigma_w^2 + r(\sigma_b^2)$
Between Replicates	p(r-1) = 12	16	1.3	σ_w^2
Total	pr – 1 = 17	2475398	NA	NA

Note: Units used for the analysis were frequency difference (1/s).
[1] p = number of probes, r = number of replicate tests for each probe.
[2] σ_w^2 = variance among replicates, σ_b^2 = variance among different probes.

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14. ABSTRACT
The National Center for Asphalt Technology (NCAT) completed construction of a 2.7-km oval test track during the year 2000. The Geotechnical and Structures Laboratory (GSL) of the U.S. Army Engineer Research and Development Center (ERDC) assisted with the installation of instrumentation for environmental monitoring. This report documents the calibration and installation of moisture probes, temperature probes, and tipping buckets. The moisture probes were placed beneath the pavement structure, near the top of select fill material. The temperature probes were placed at various depths in the asphalt concrete. The tipping buckets were positioned at subsurface drainage outlets. The collaboration between GSL, NCAT, and a private consultant resulted in the successful installation of 23 dataloggers, 184 temperature probes, 29 moisture probes, and 3 tipping buckets.

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